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Hansen

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(54) **METHOD FOR OPTICAL SYSTEM COHERENCE TESTING**

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(73) Assignee: **ASML Holding N.V.** (NL)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 452 days.

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(22) Filed: **Jul. 6, 2001**

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US 2002/0027662 A1 Mar. 7, 2002

Related U.S. Application Data

(63) Continuation-in-part of application No. 09/783,406, filed on Feb. 15, 2001, now abandoned.

(60) Provisional application No. 60/182,510, filed on Feb. 15, 2000.

(51) **Int. Cl.**^{7} **G01B 9/02**

(52) **U.S. Cl.** **356/521**; 356/450

(58) **Field of Search** 356/521, 450, 356/477, 478, 520, 550; 250/550

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(74) *Attorney, Agent, or Firm*—Sterne, Kessler, Goldstein & Fox P.L.L.C.

(57) **ABSTRACT**

The present invention is directed at a coherence test reticle or lithographic plate, and a method for testing the coherence of a laser beam using the test reticle. The quality or coherence of the laser beam is measured by illuminating the test reticle and the recording and/or analyzing the optical patterns generated by the illumination. The technique was designed for, but not limited to, the characterization of laser-based systems via the detection of optical radiation modulated by transmissive, reflective and diffractive patterns printed on a reticle or lithographic plate designed specifically for this purpose. The novelty and advantages over the prior art are insensitivity to vibration, alignment, and multi-path differences of classical interferometric coherence measurement techniques. Spatial coherence and longitudinal or temporal coherence may be measured independently. Vertical and horizontal coherence may be measured independently. The technique is focus error insensitive. That is to say, that focus errors will be recorded by the technique in a deterministic fashion and can be removed from the data. The robustness and convenience of the technique is driven by the single plate with no optical alignment, making the technique easily implemented in the field. The multiplexing of the feature orientations, sizes and line types and feature locations allows for the determination of coherence parameters as a function of position in the beam.

14 Claims, 12 Drawing Sheets

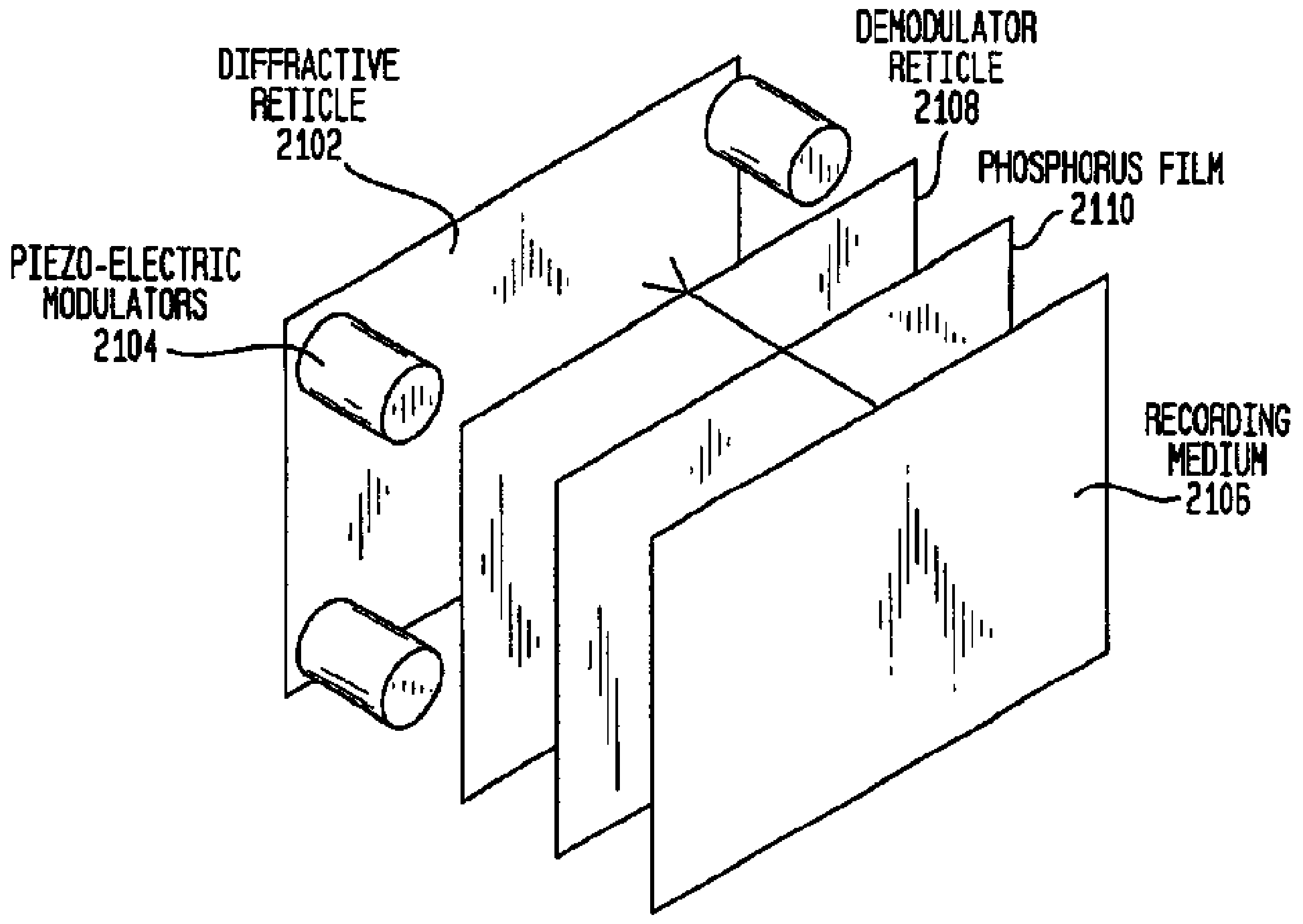

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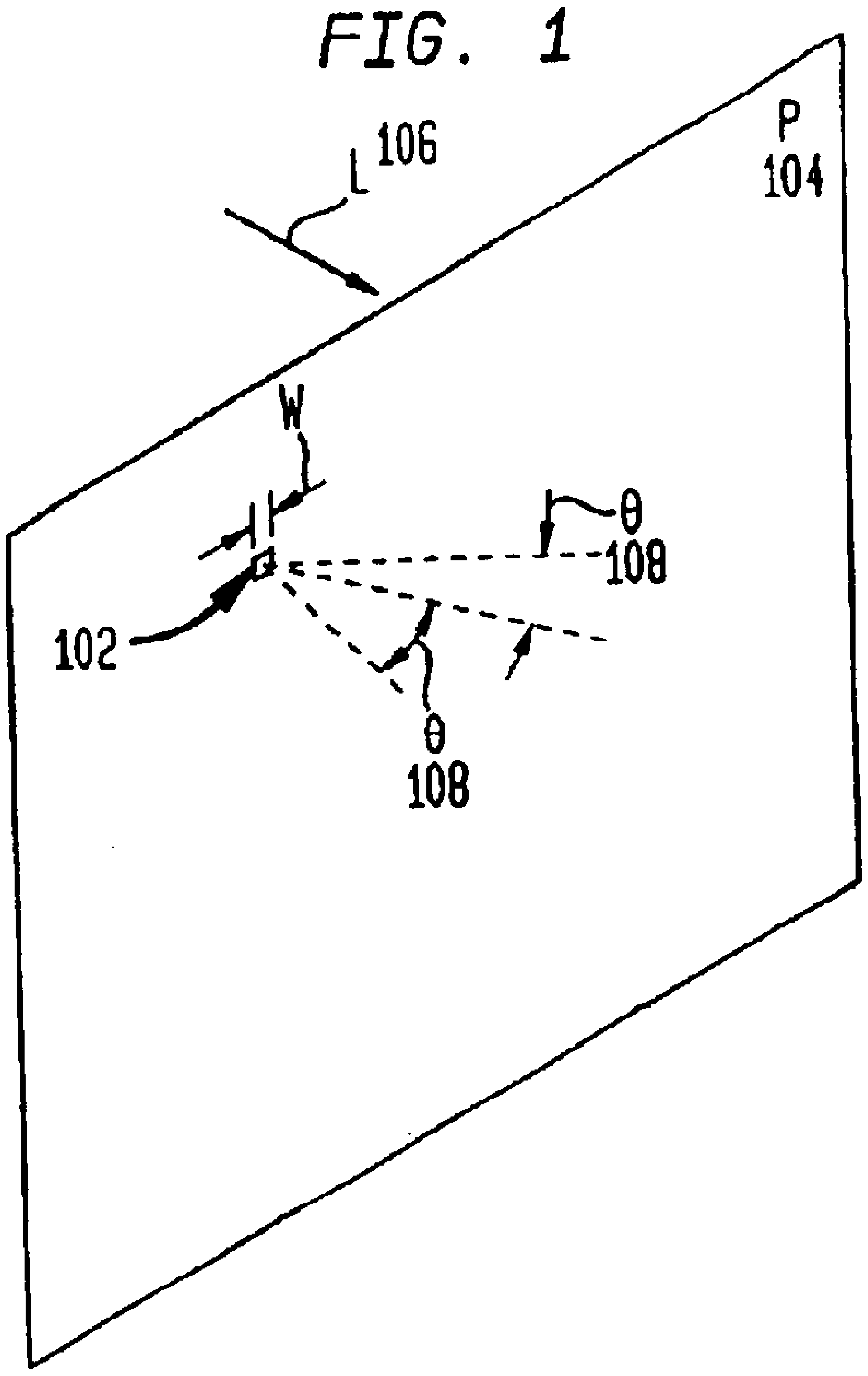
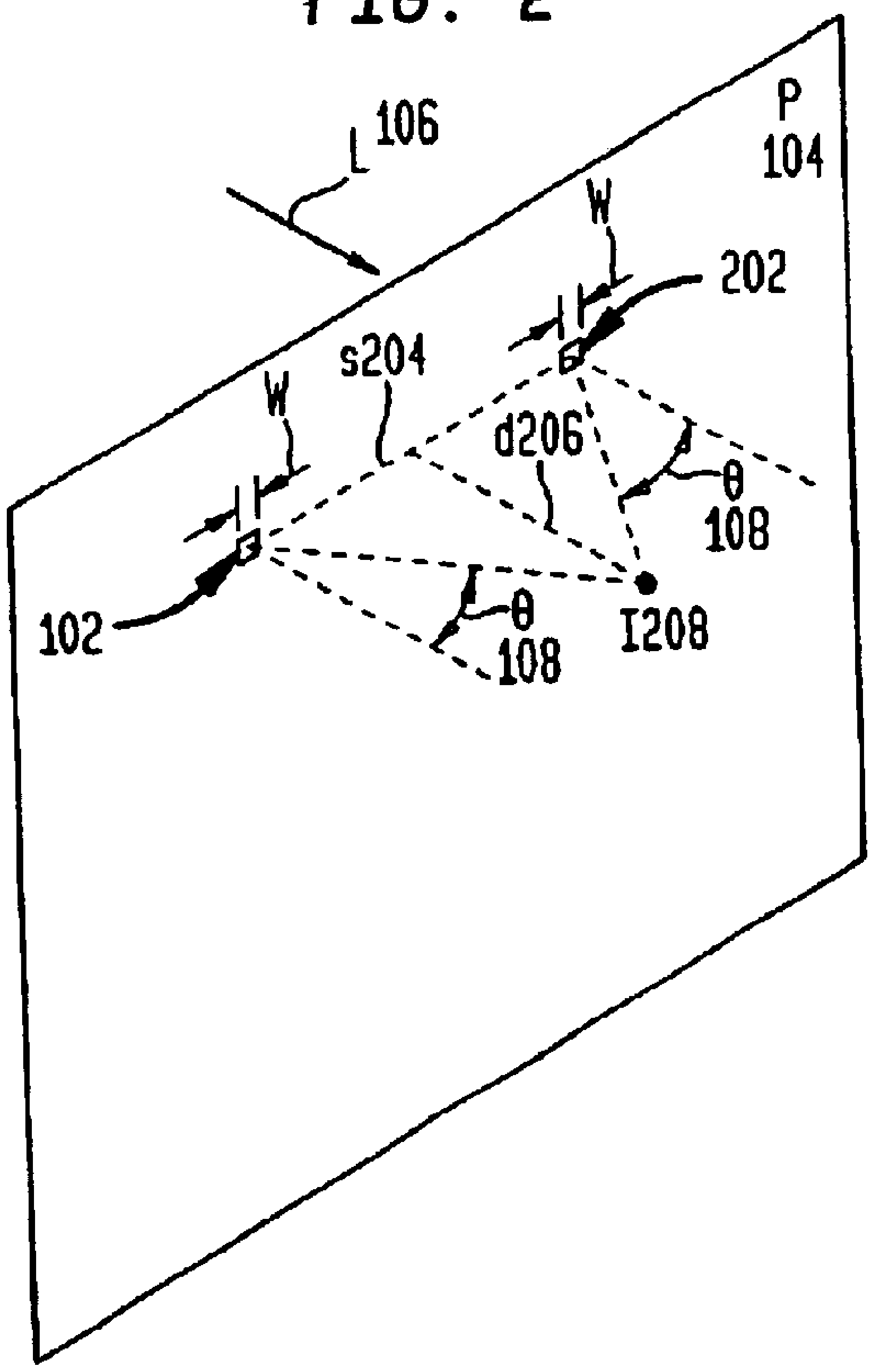
FIG. 1



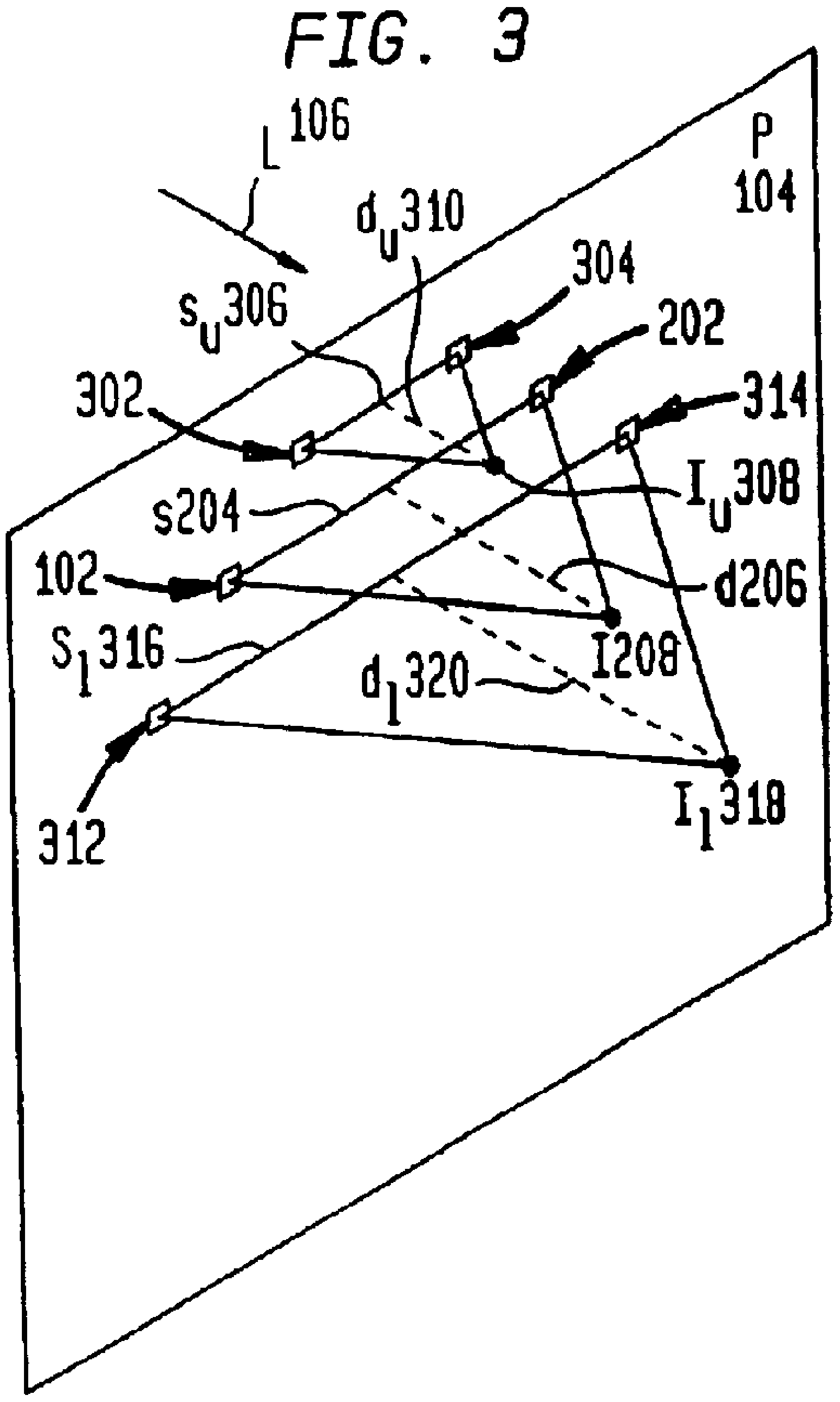
PRIOR ART

FIG. 2



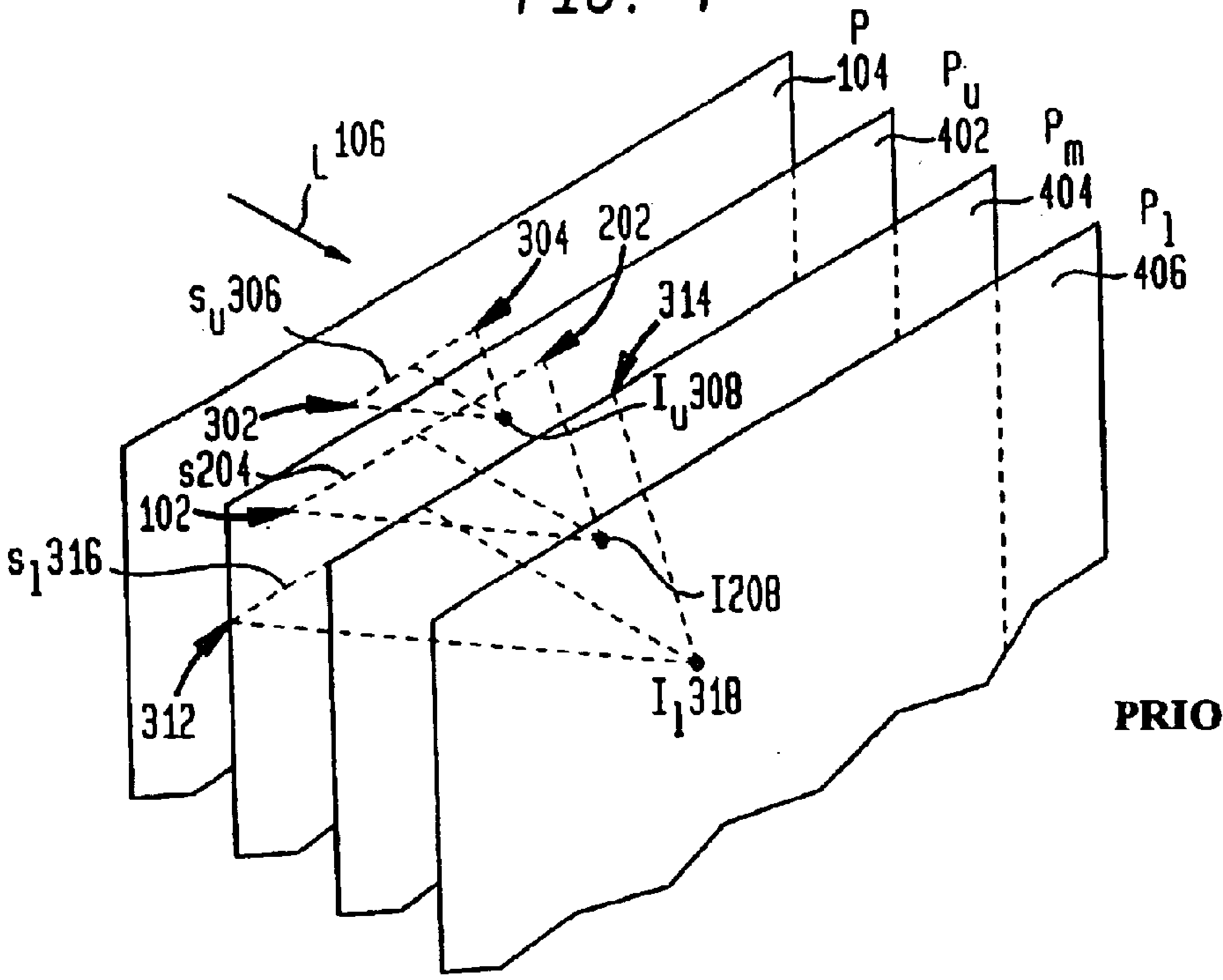
PRIOR ART

FIG. 3



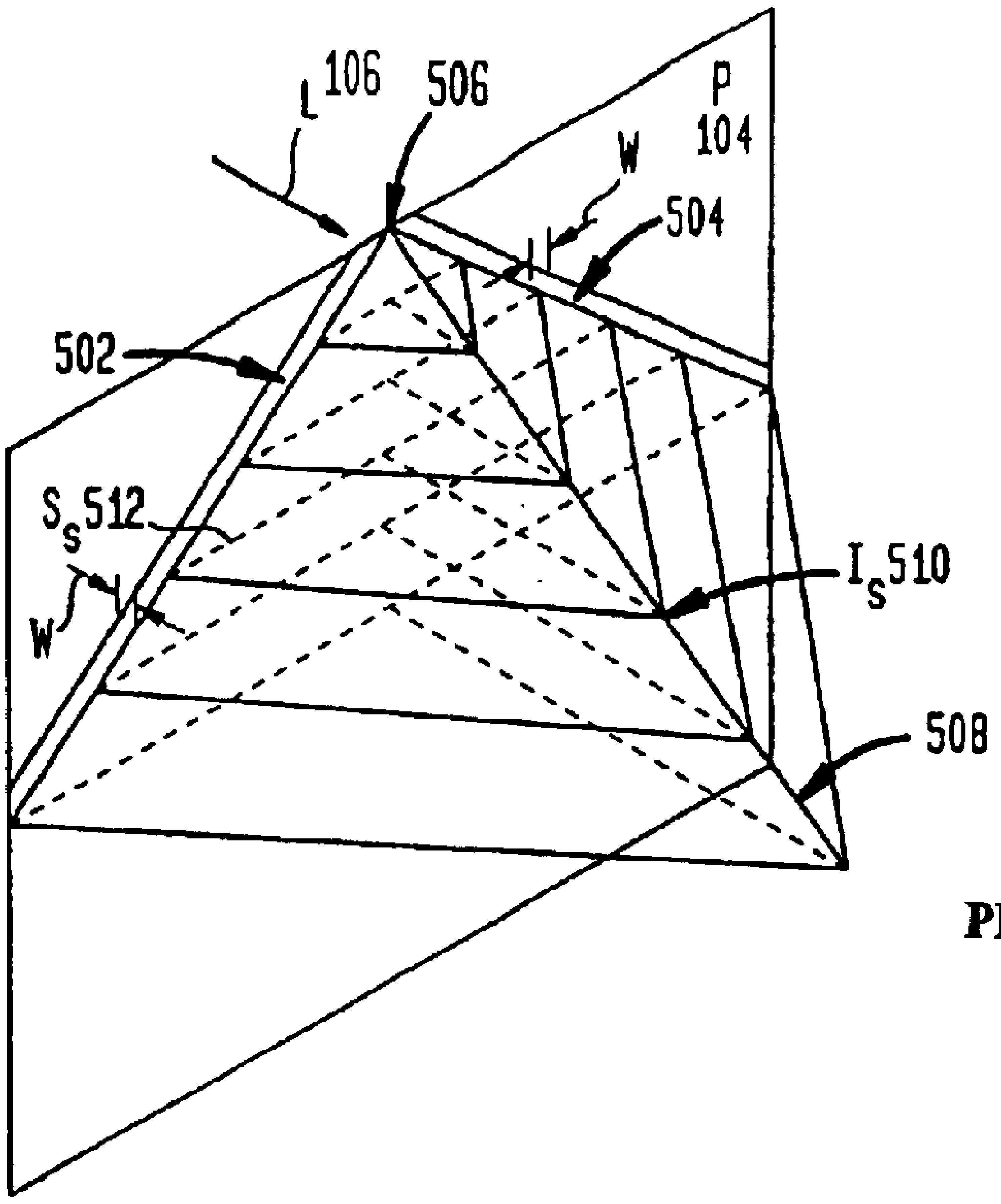
PRIOR ART

FIG. 4



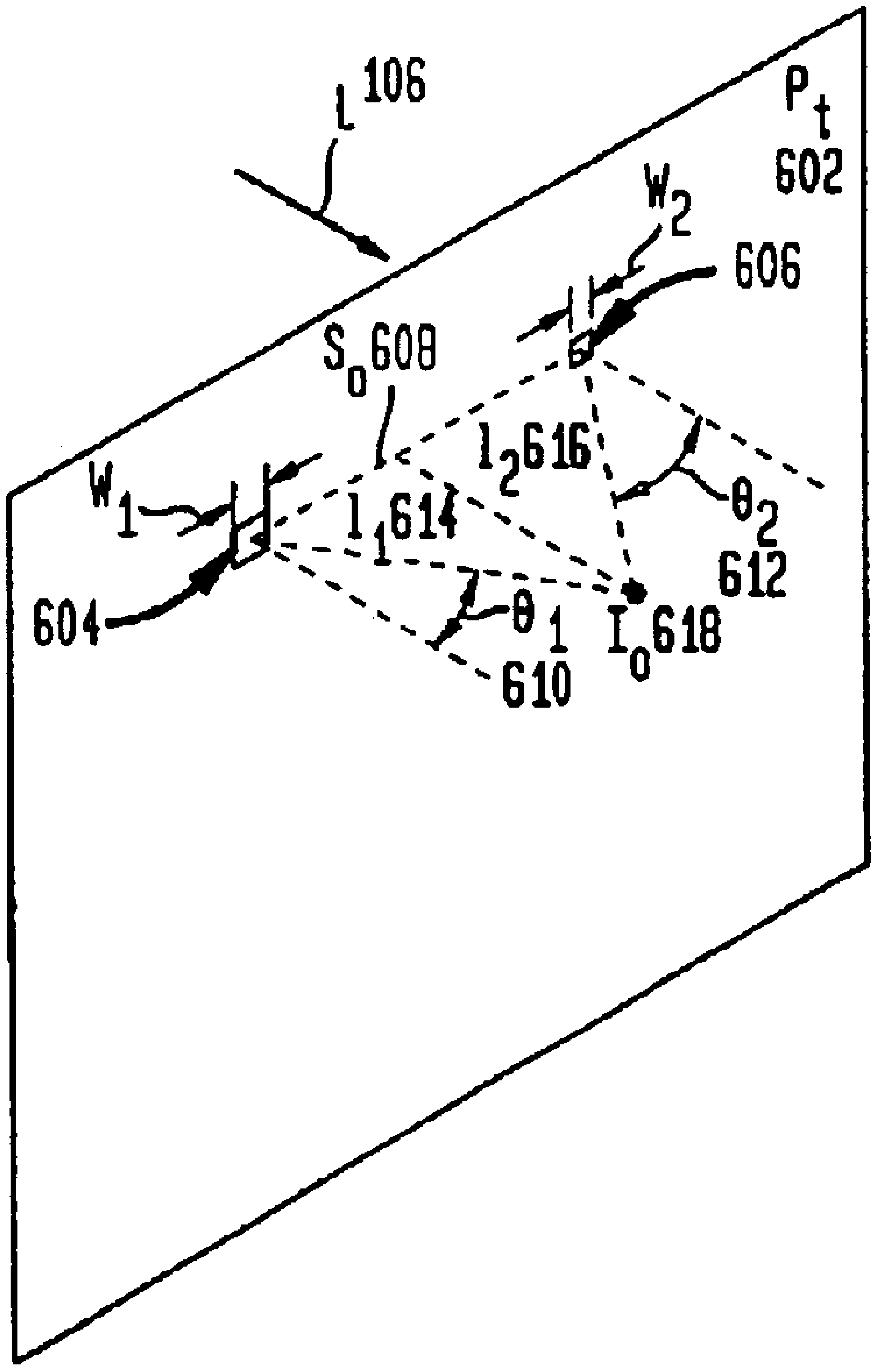
PRIOR ART

FIG. 5



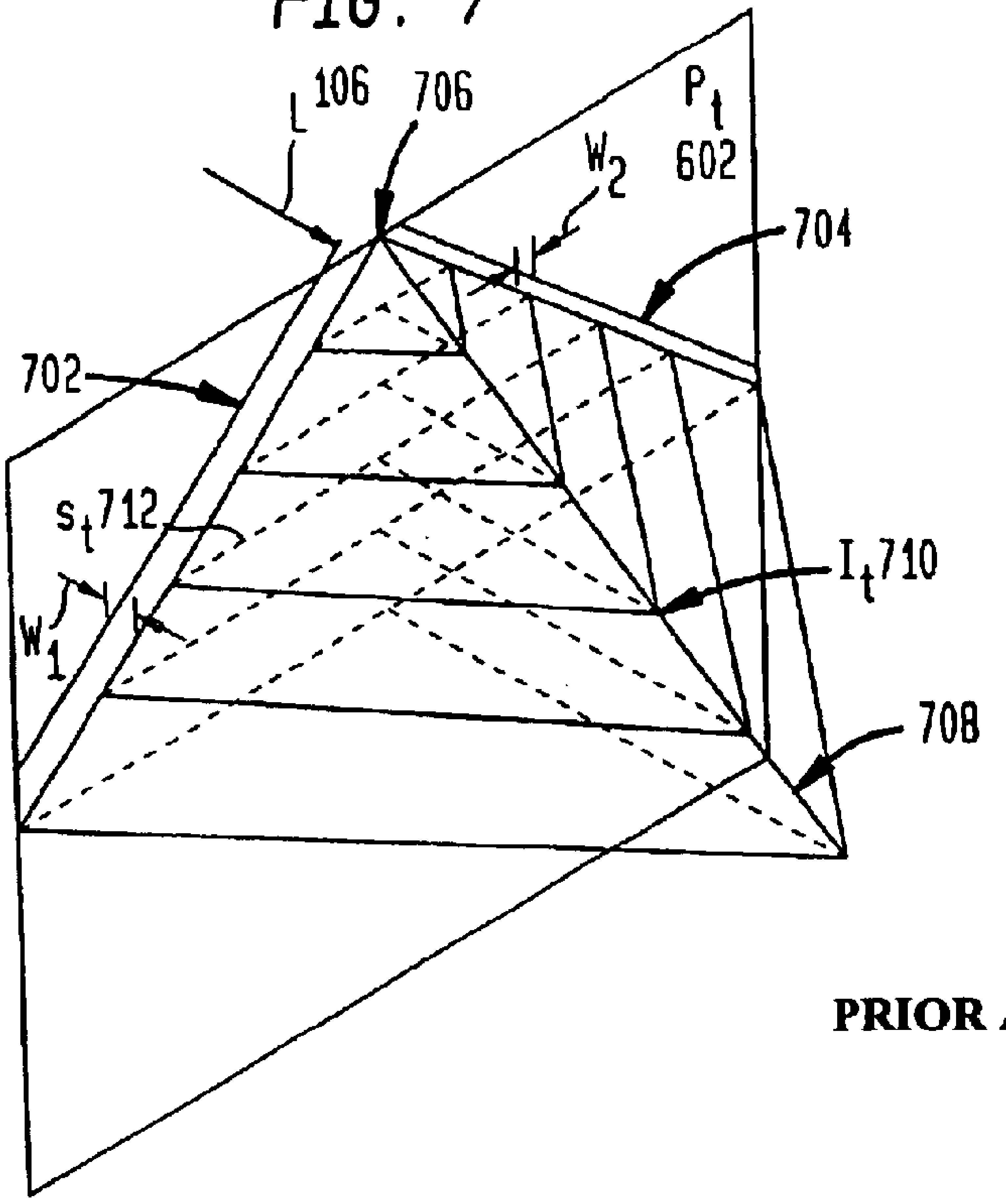
PRIOR ART

FIG. 6



PRIOR ART

FIG. 7



PRIOR ART

FIG. 8

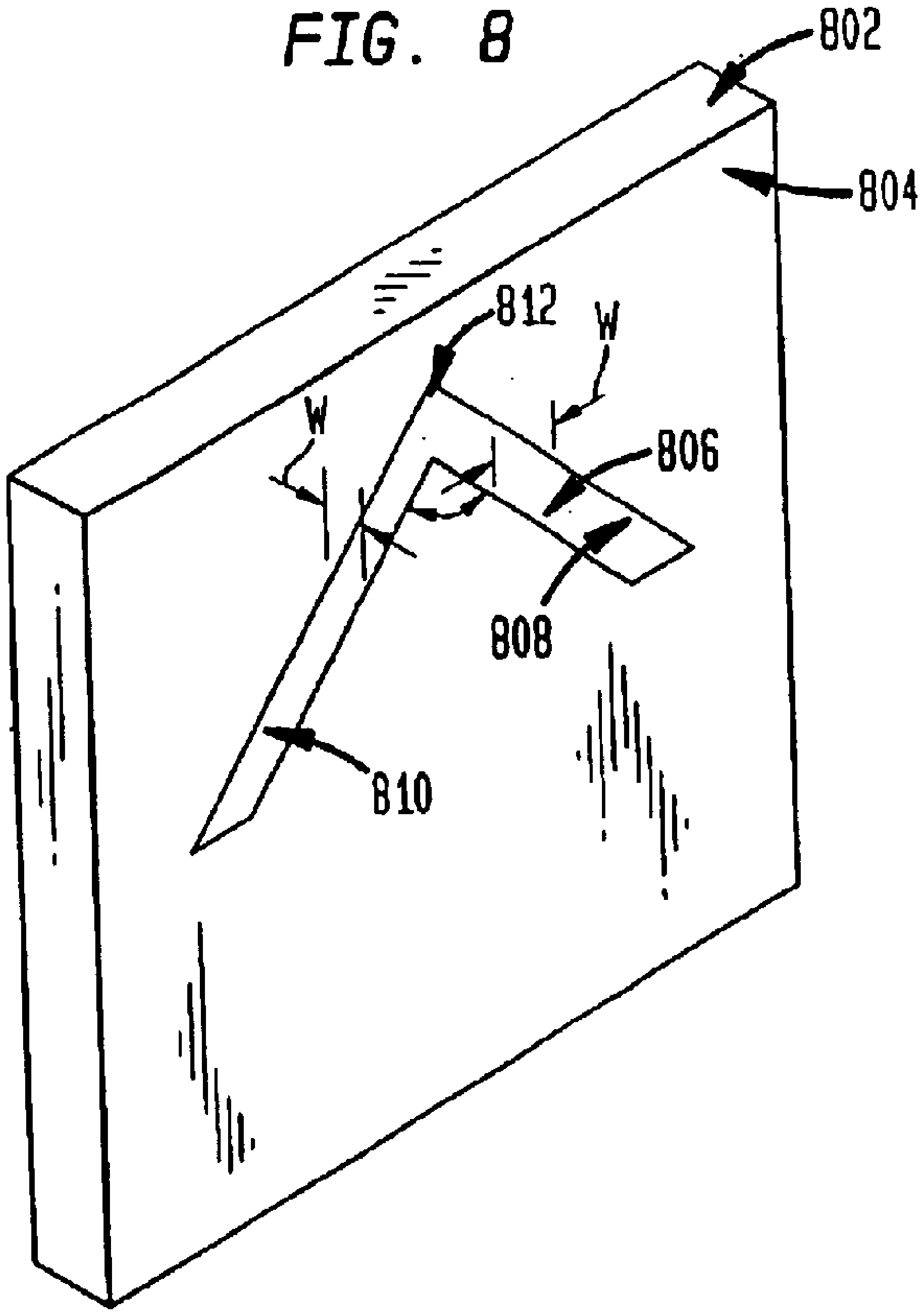


FIG. 9

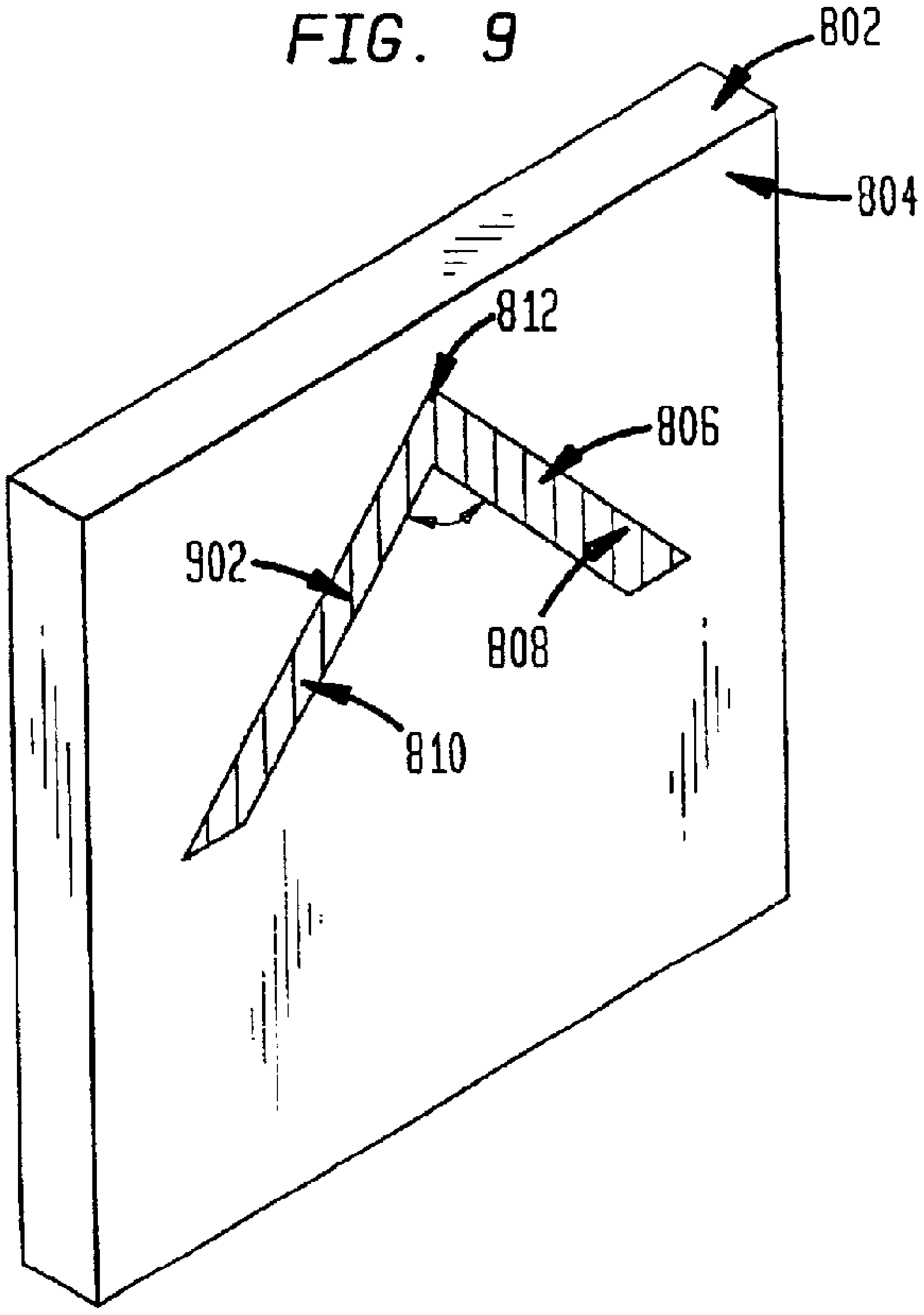


FIG. 10

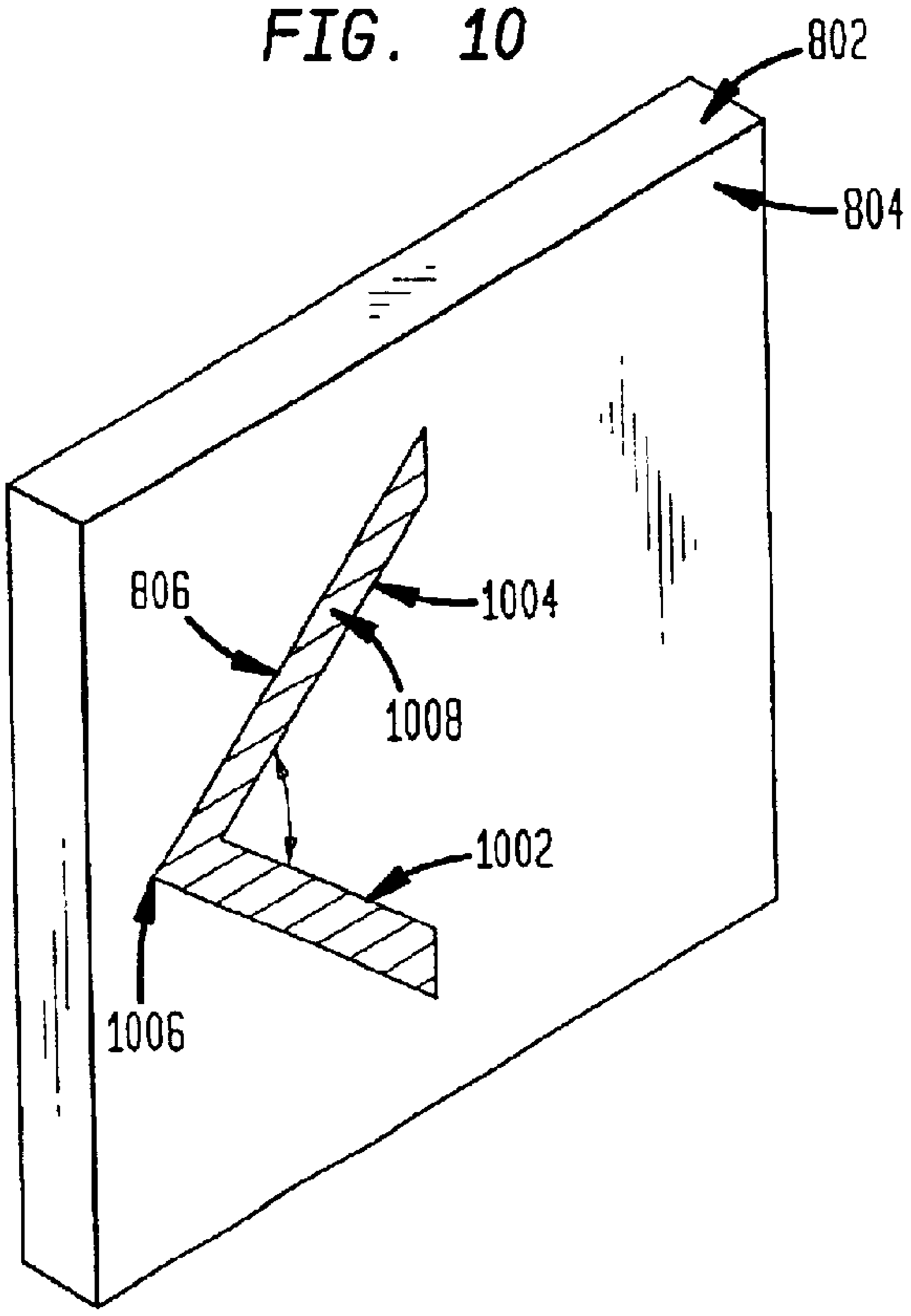


FIG. 11

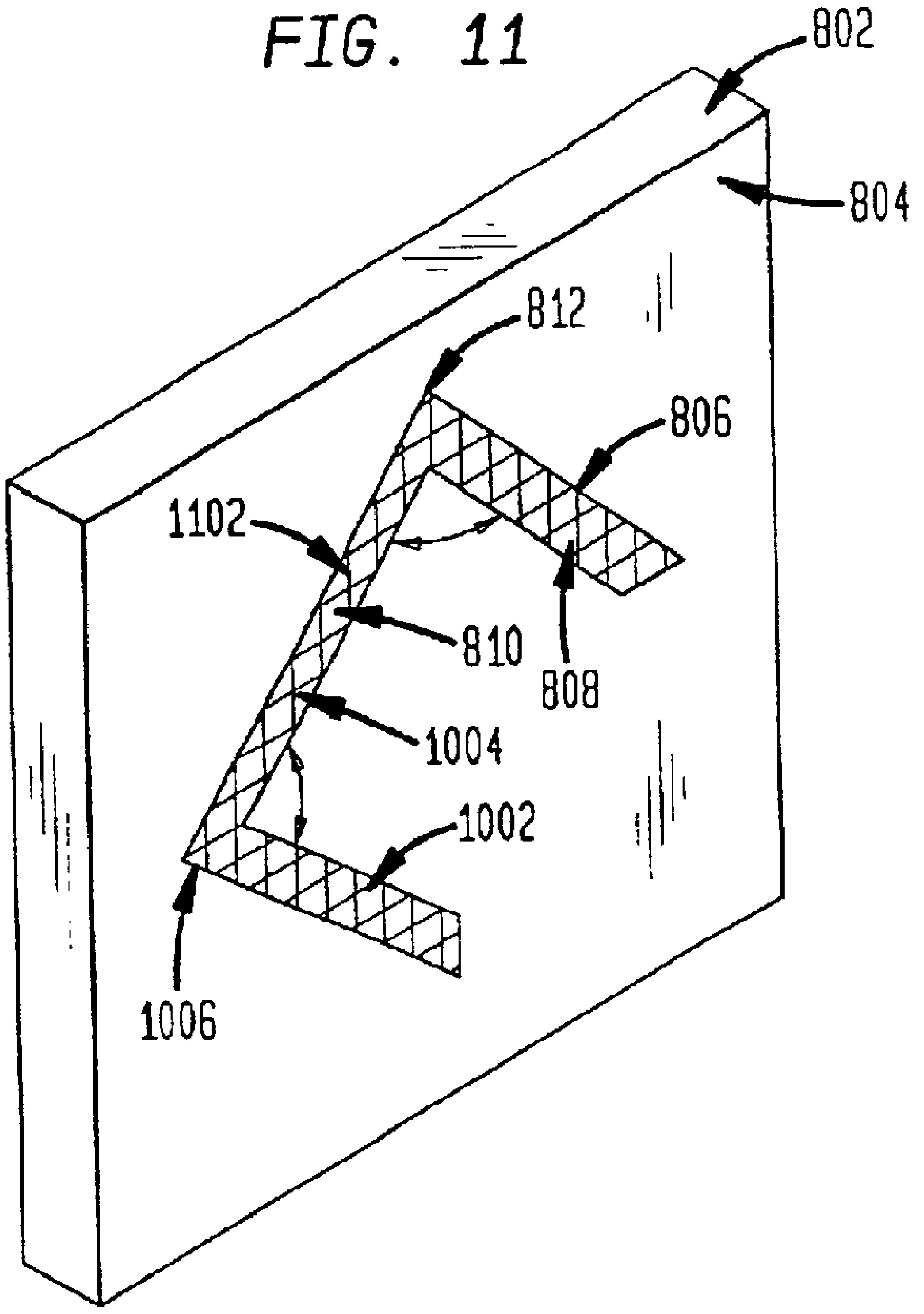

802
804
812
806
1102
810
808
1004
1002
1006

FIG. 12

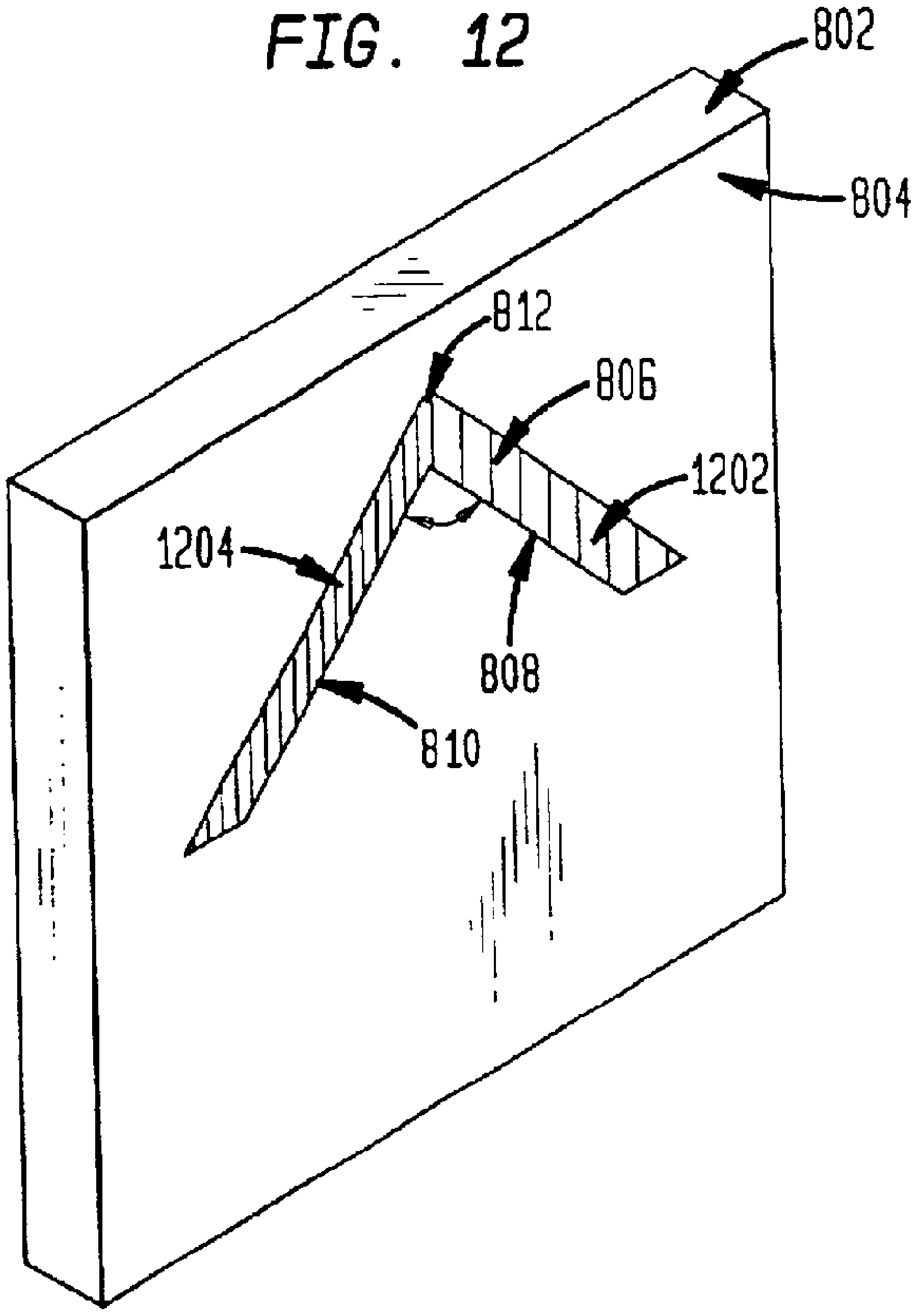
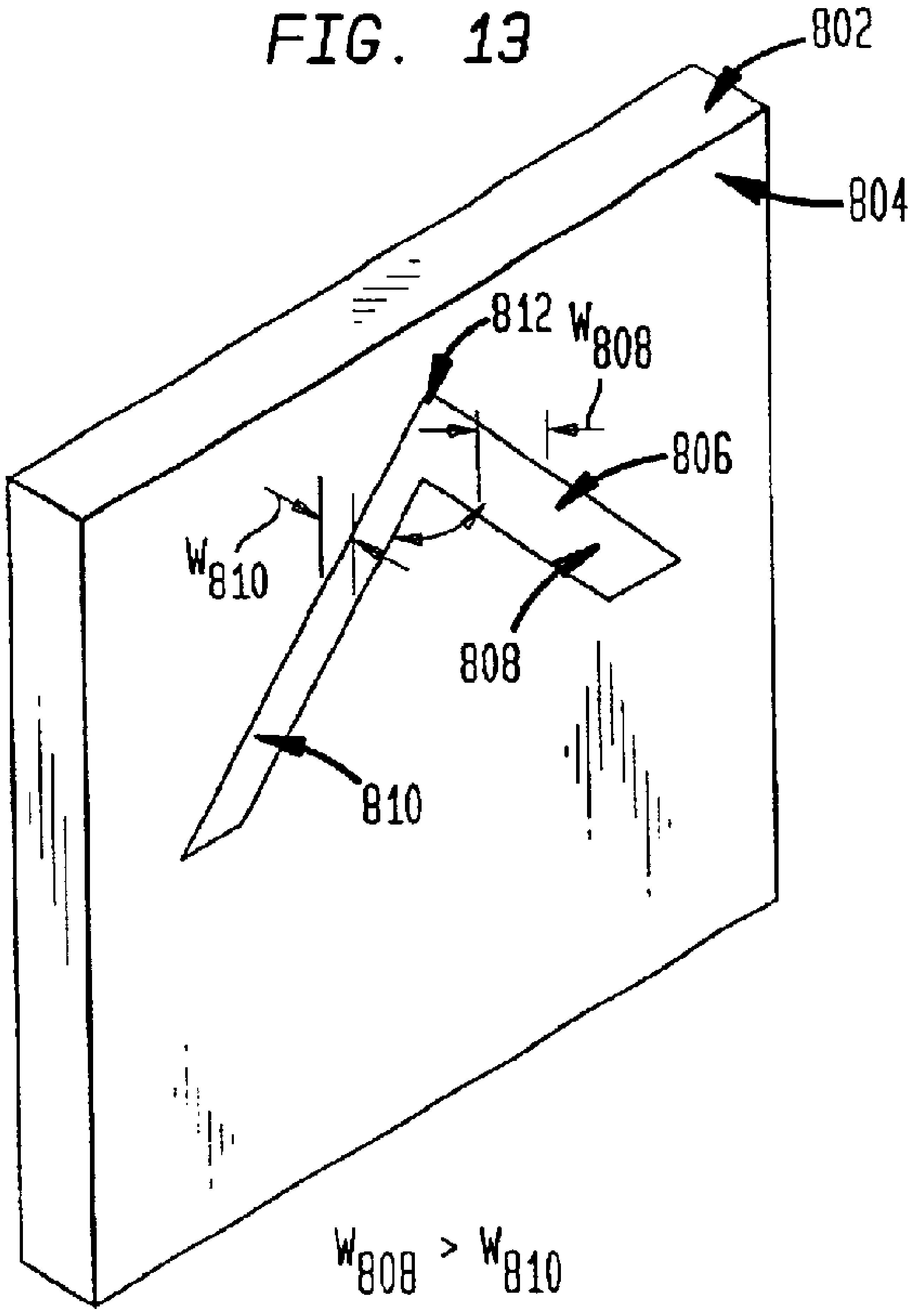
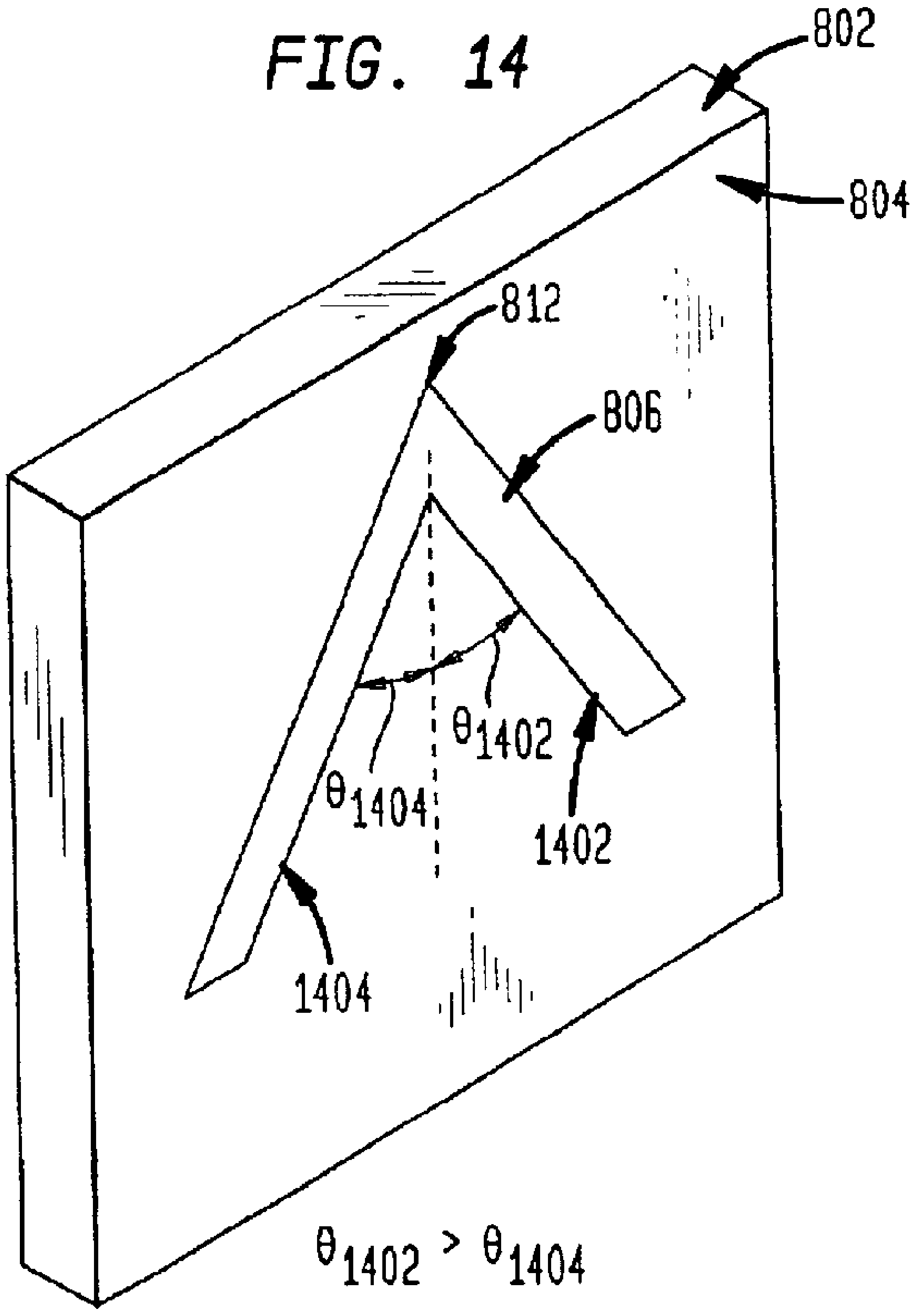

802
804
812
806
1202
1204
808
810

FIG. 13



$W_{808} > W_{810}$

FIG. 14



$\theta_{1402} > \theta_{1404}$

FIG. 15

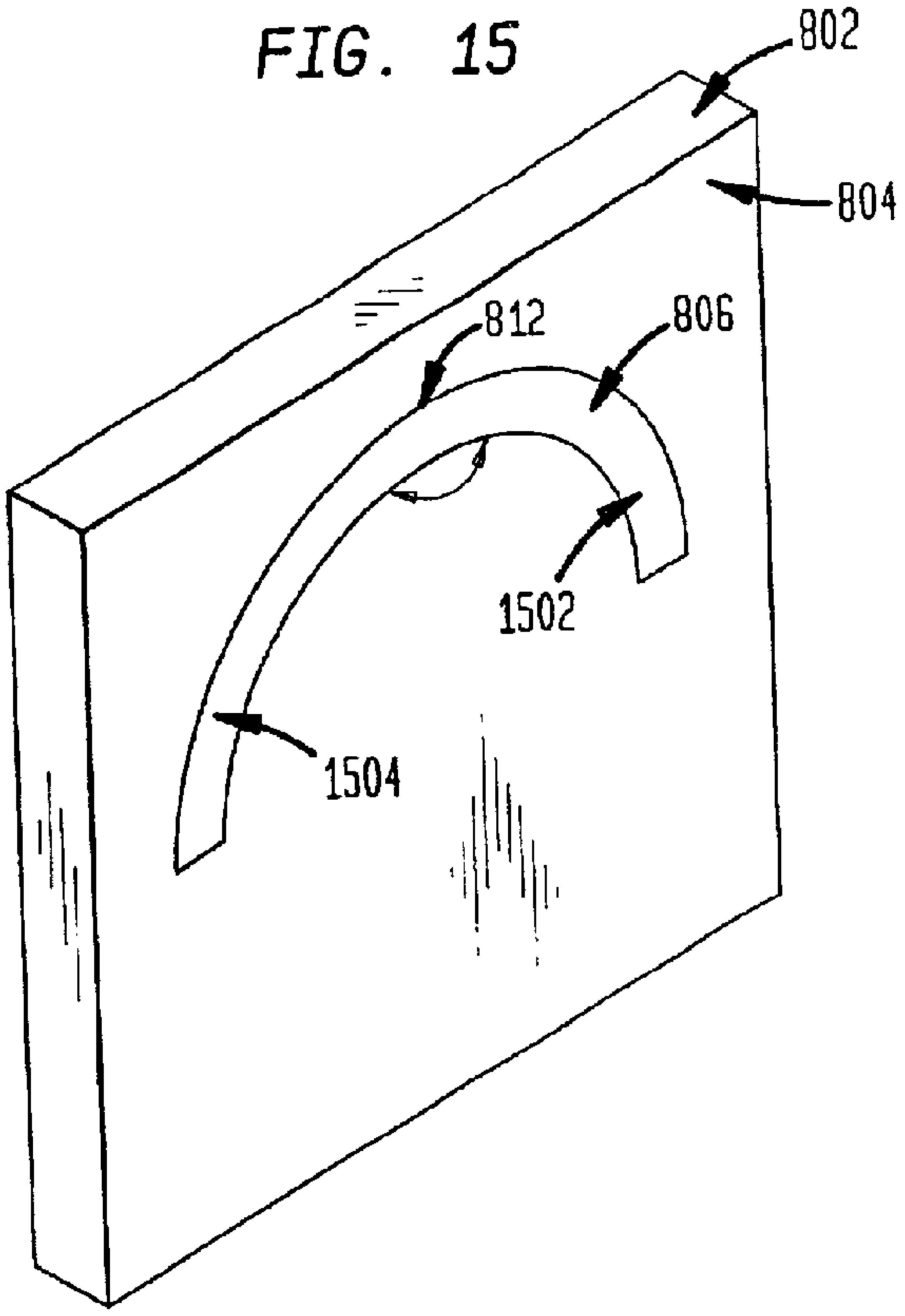


FIG. 16

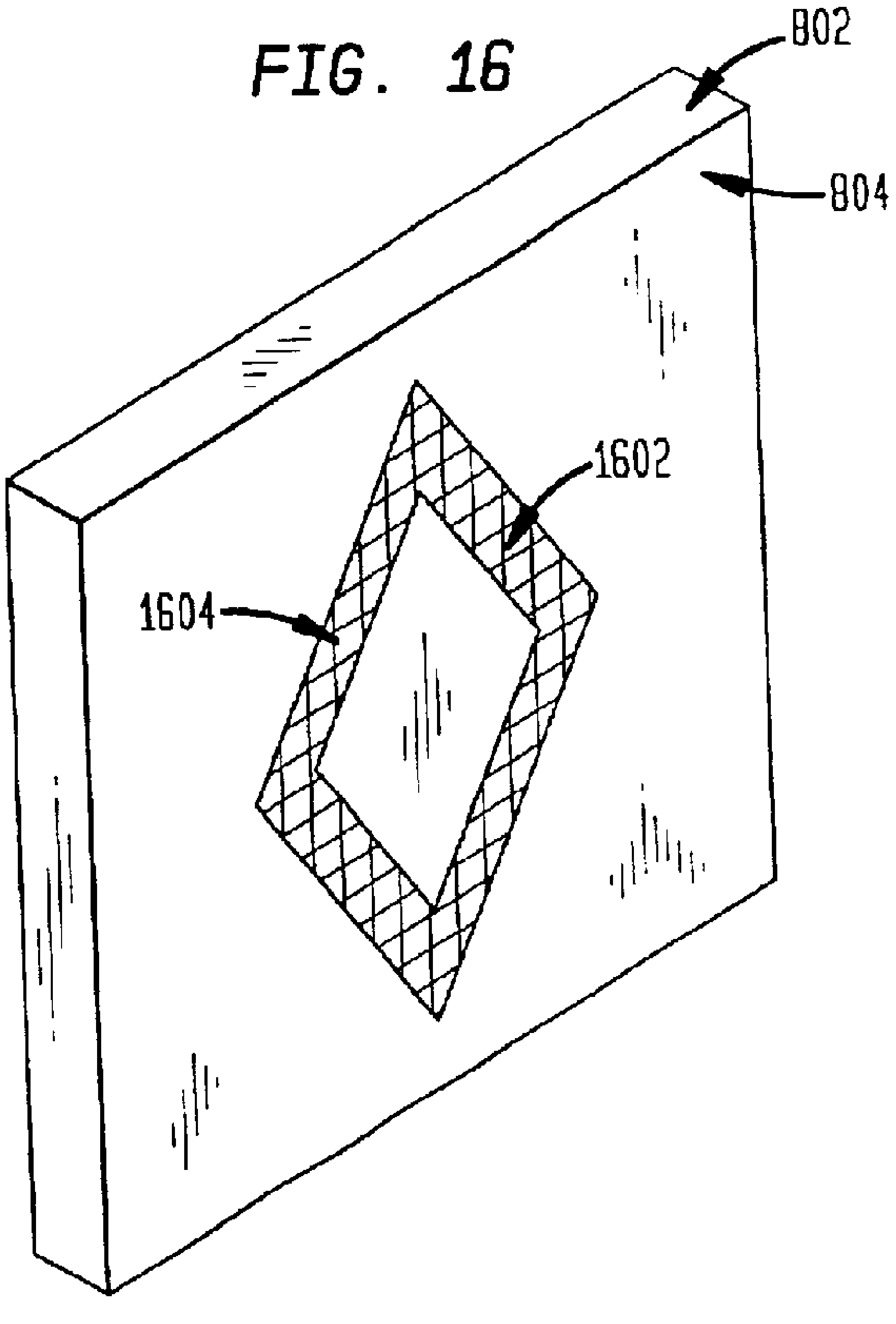


FIG. 17

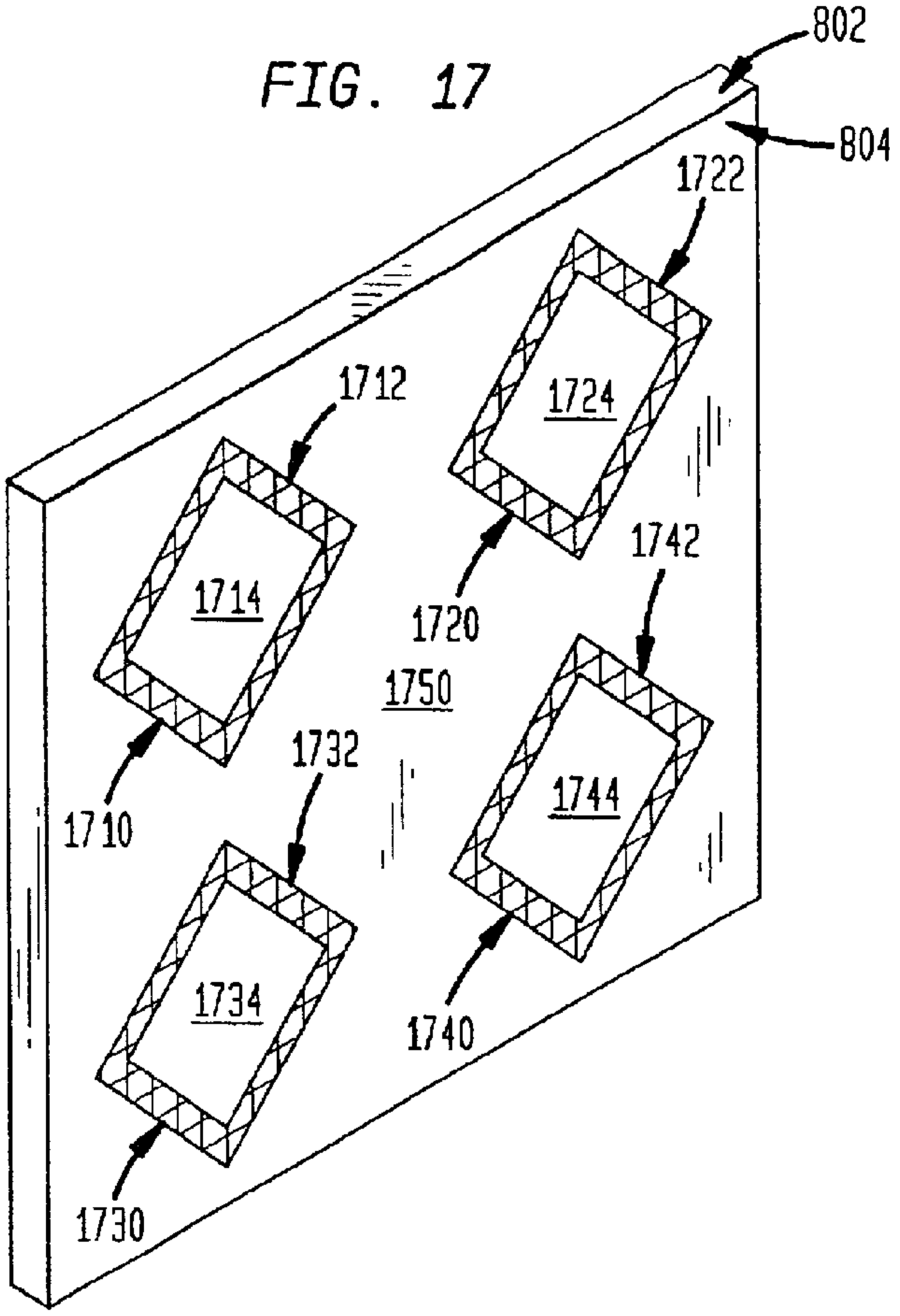

802
804
1722
1724
1712
1714
1720
1742
1750
1732
1710
1744
1740
1734
1730

FIG. 18

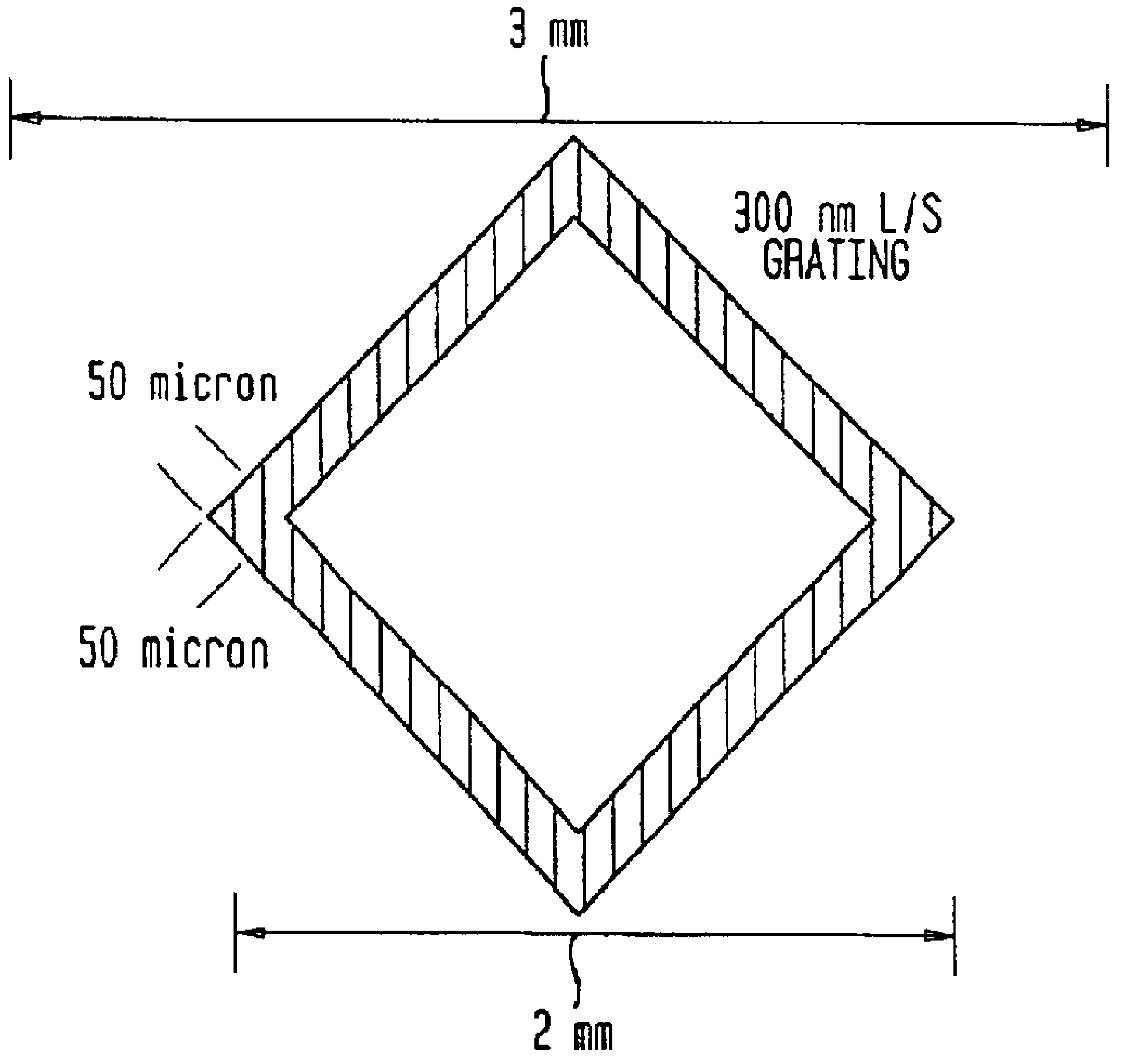

3 mm
300 nm L/S
GRATING
50 micron
50 micron
2 mm

FIG. 19

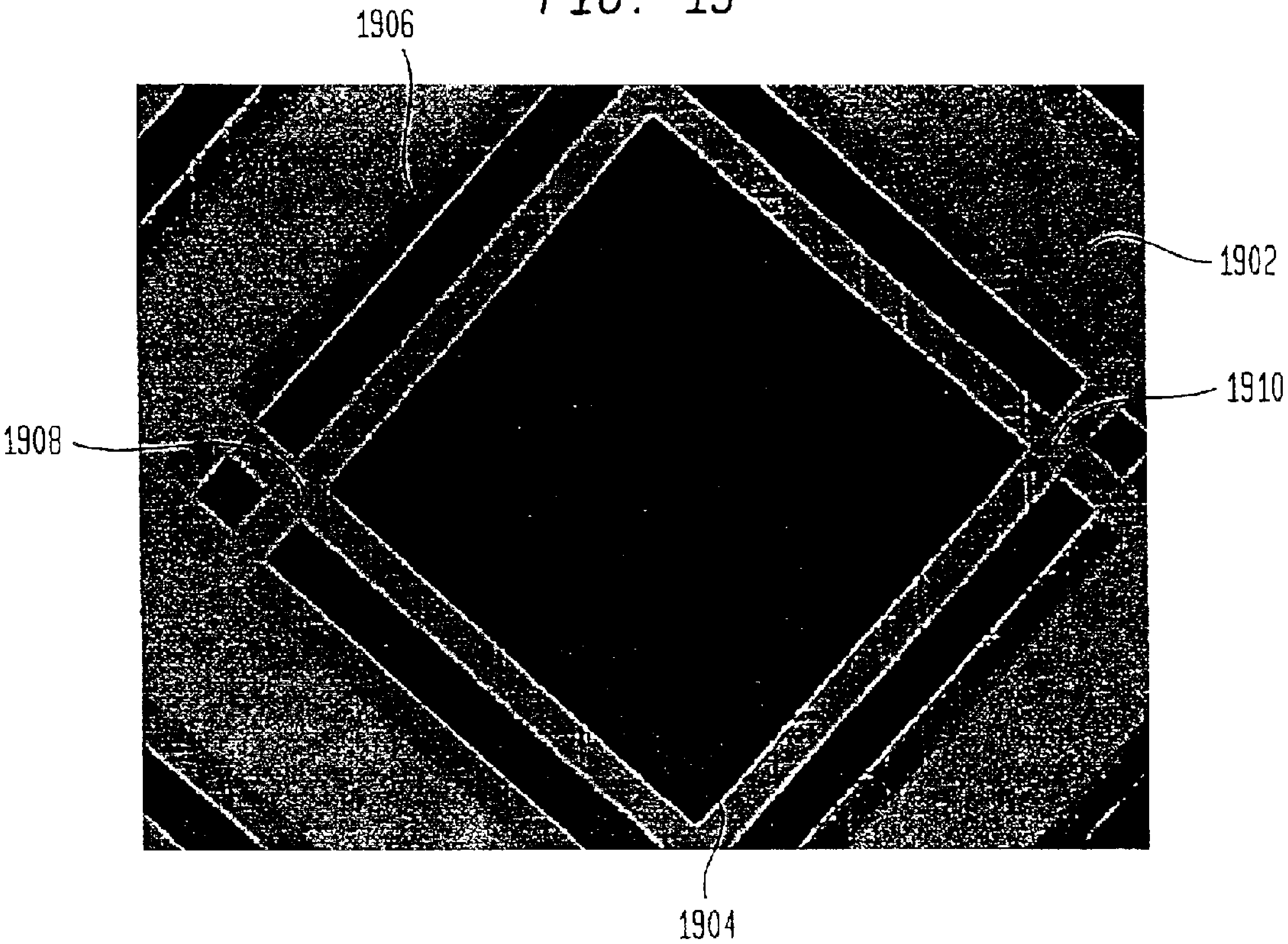


FIG. 20

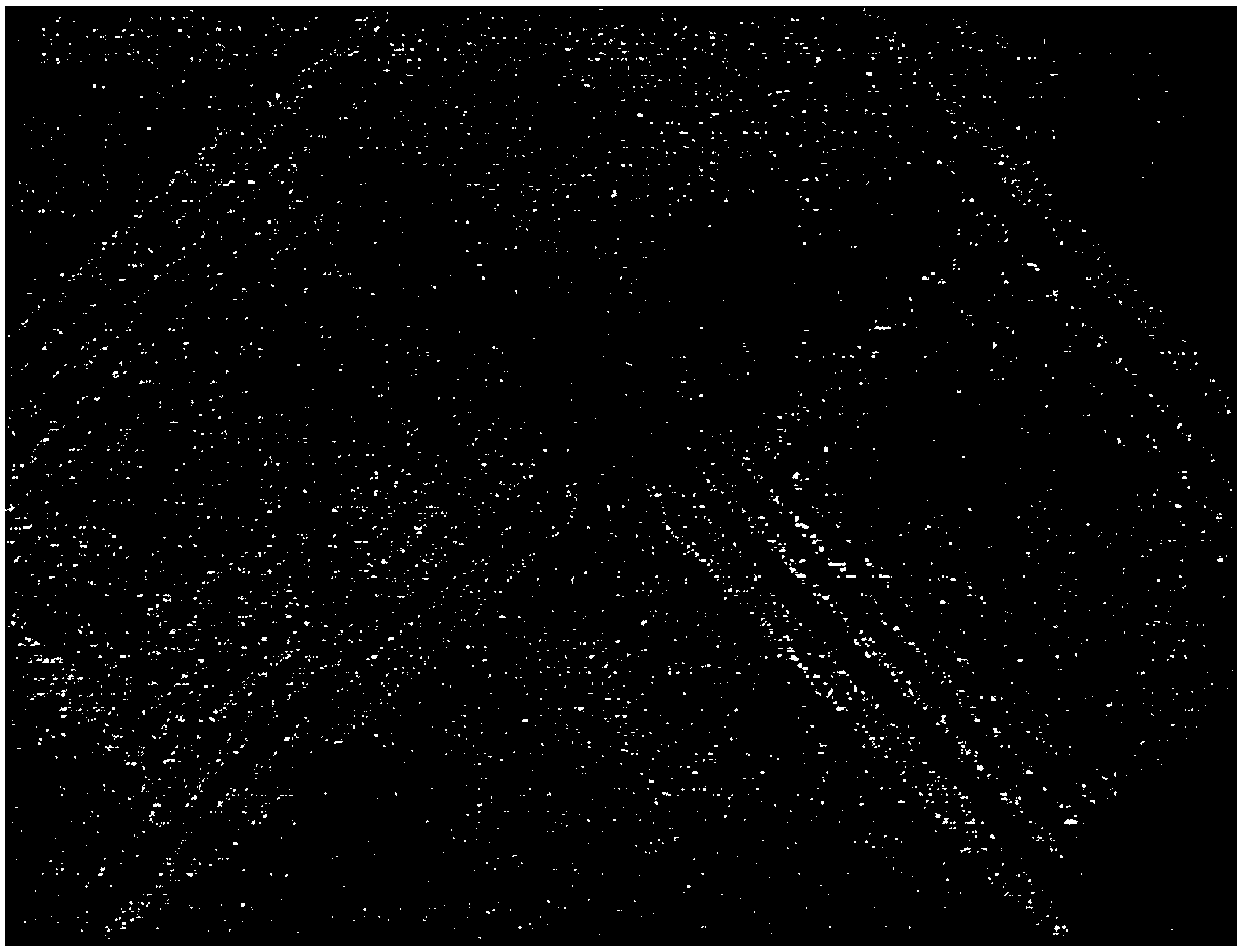


FIG. 21

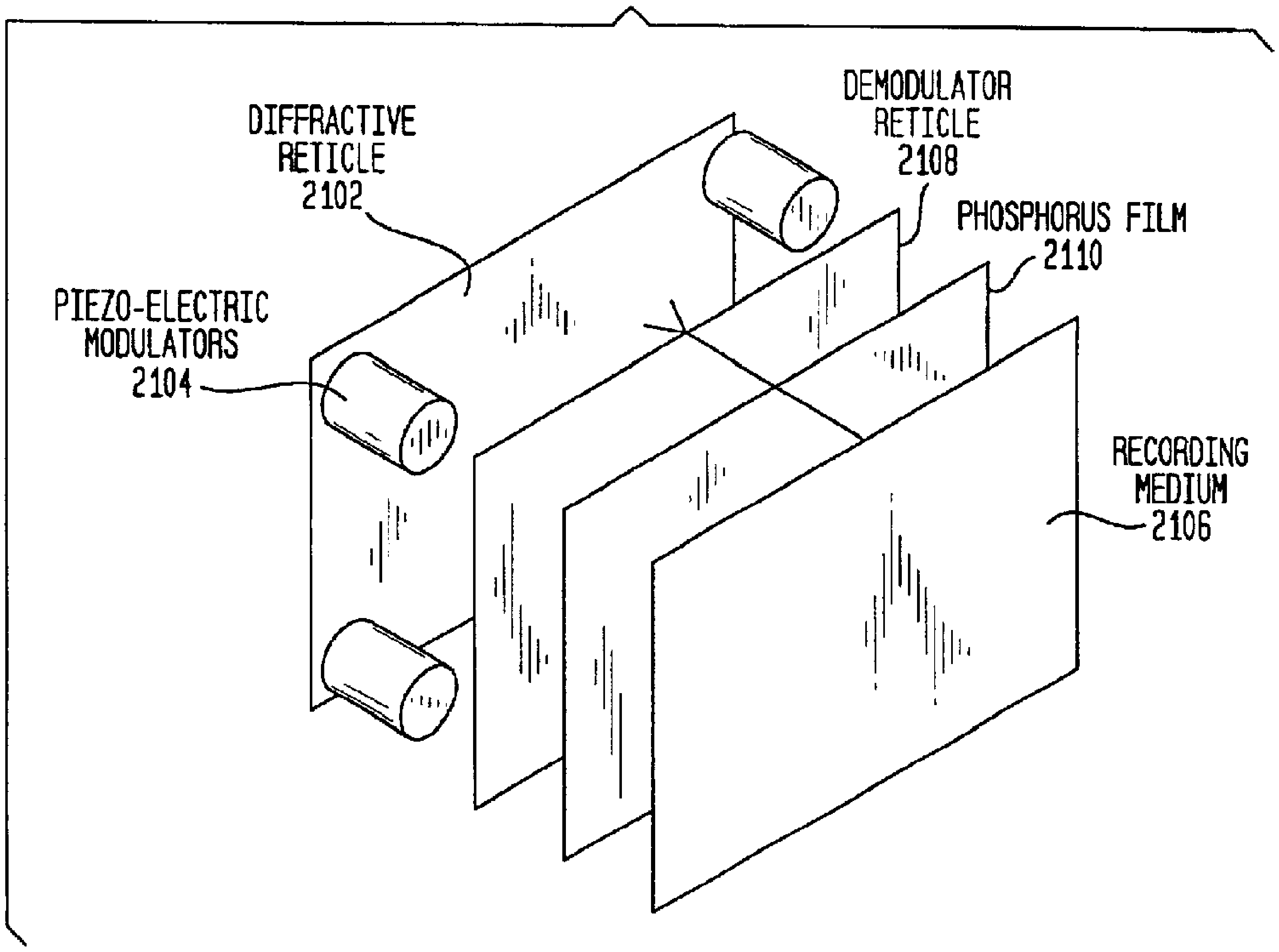

DIFFRACTIVE RETICLE 2102
DEMODULATOR RETICLE 2108
PHOSPHORUS FILM 2110
PIEZO-ELECTRIC MODULATORS 2104
RECORDING MEDIUM 2106

FIG. 22

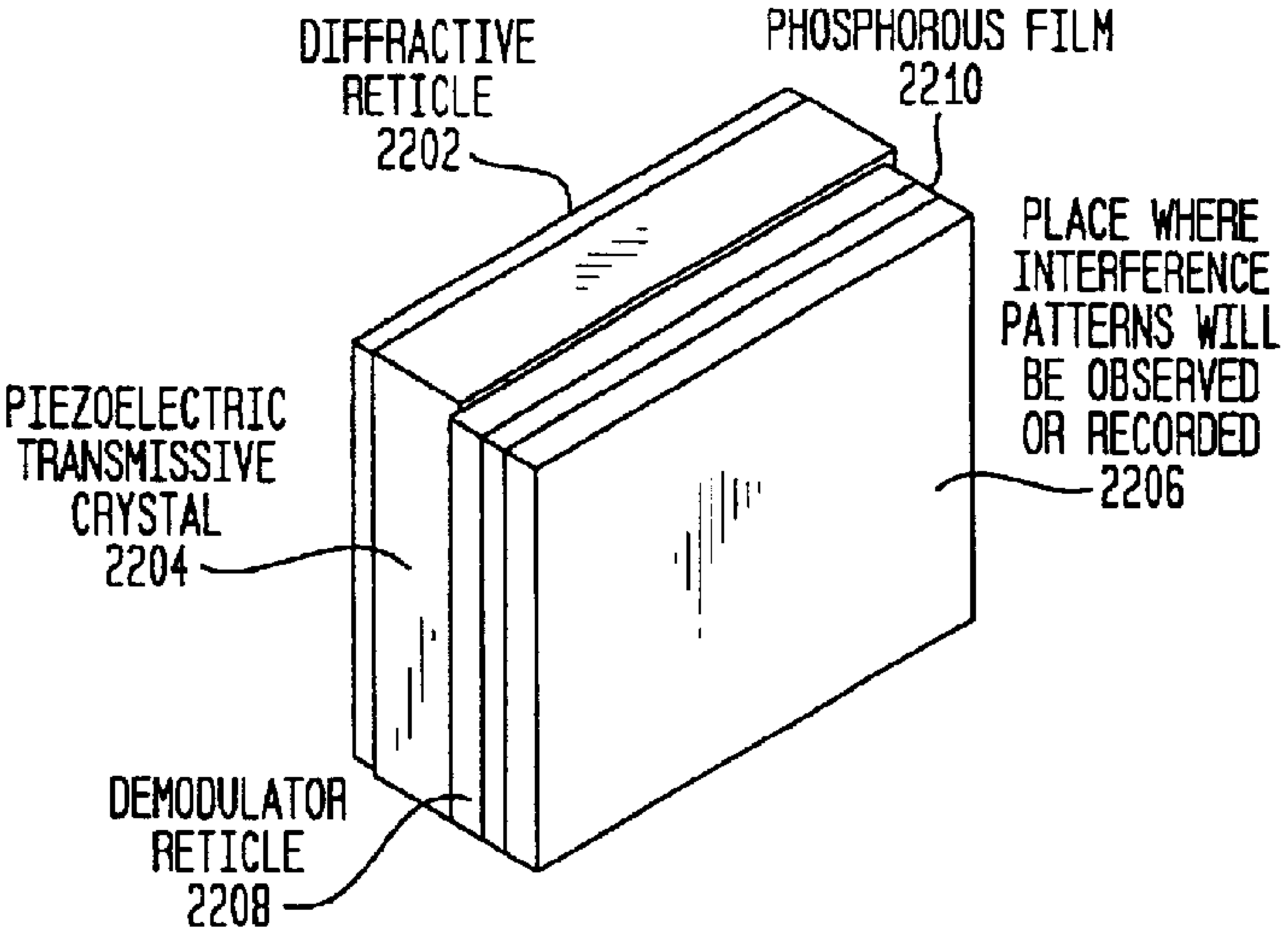

DIFFRACTIVE RETICLE 2202
PHOSPHOROUS FILM 2210
PLACE WHERE INTERFERENCE PATTERNS WILL BE OBSERVED OR RECORDED 2206
PIEZOELECTRIC TRANSMISSIVE CRYSTAL 2204
DEMODULATOR RETICLE 2208

FIG. 23

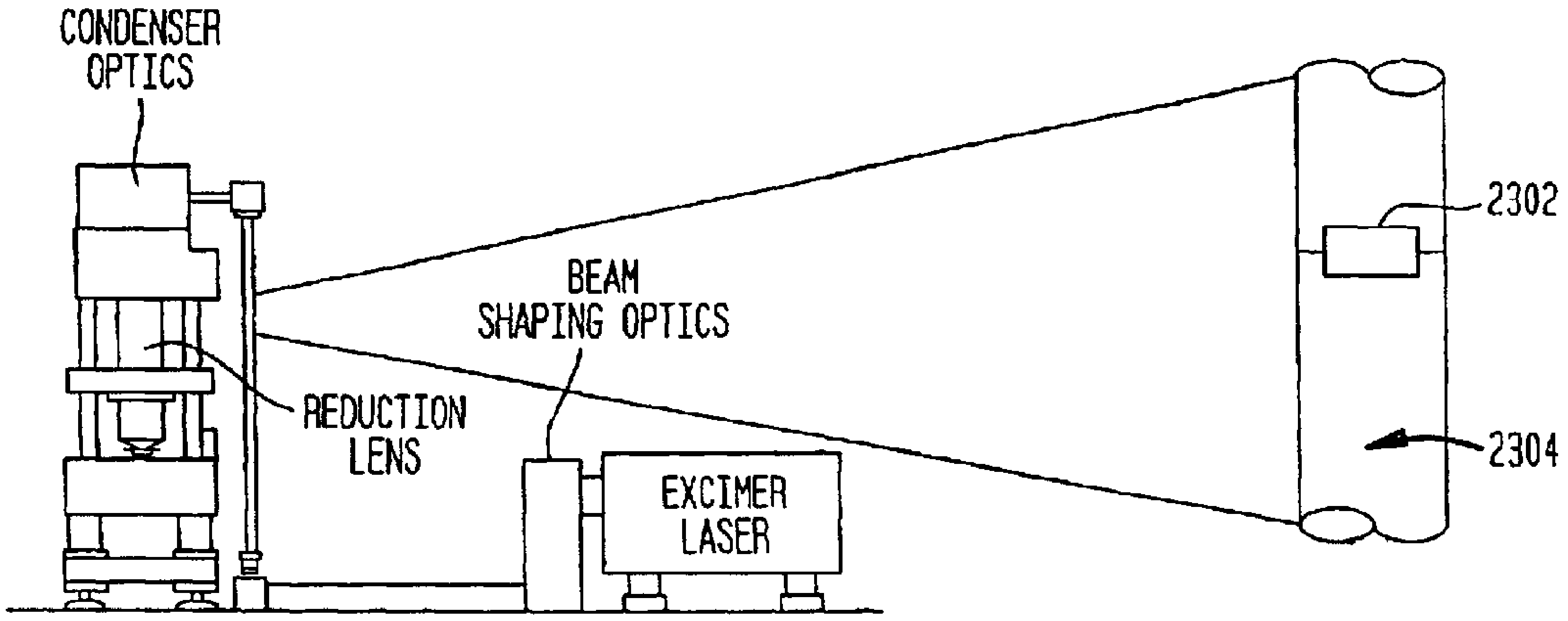
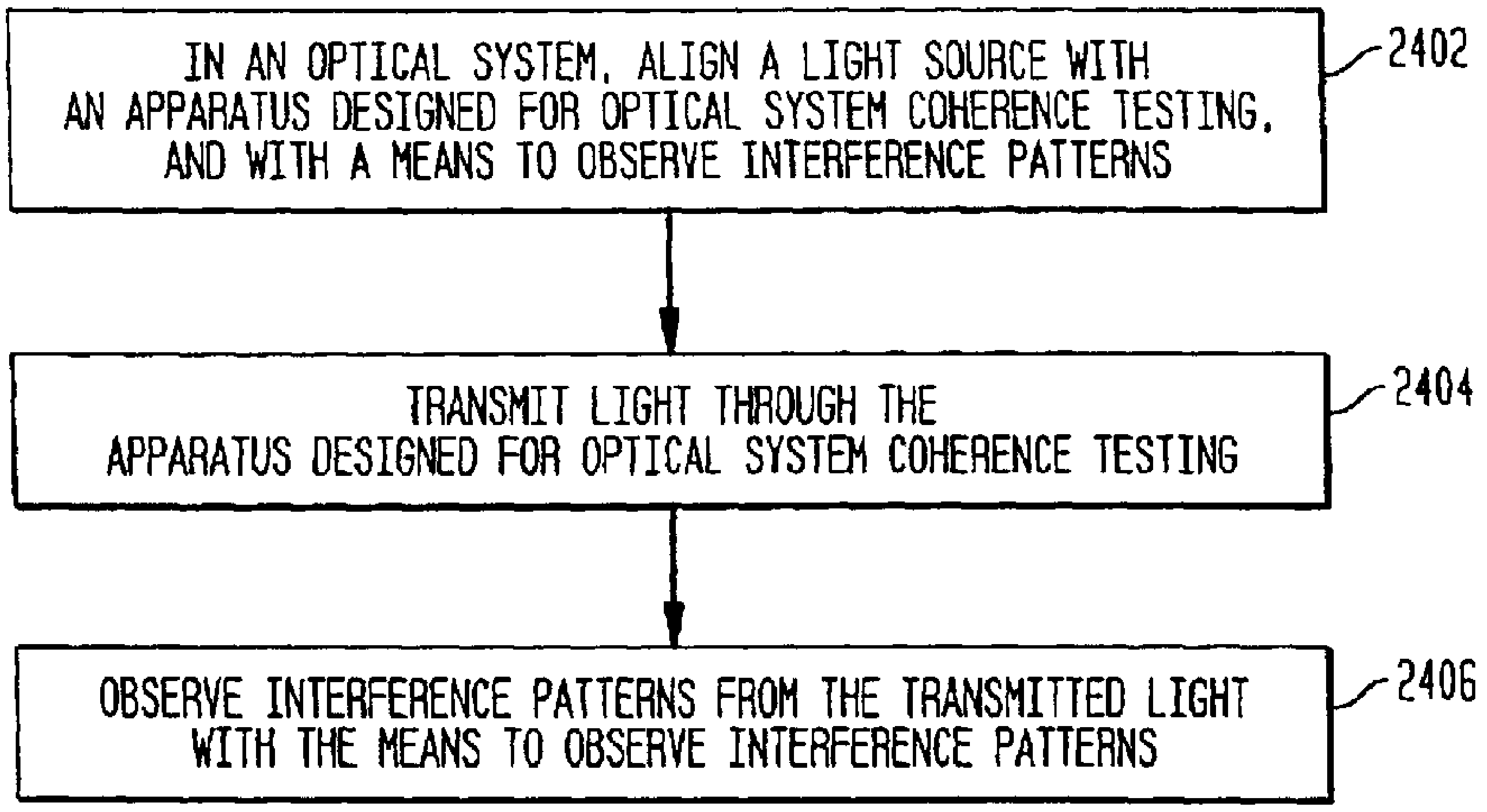

CONDENSER OPTICS
BEAM SHAPING OPTICS
REDUCTION LENS
EXCIMER LASER
2302
2304

FIG. 24


IN AN OPTICAL SYSTEM, ALIGN A LIGHT SOURCE WITH AN APPARATUS DESIGNED FOR OPTICAL SYSTEM COHERENCE TESTING, AND WITH A MEANS TO OBSERVE INTERFERENCE PATTERNS
2402
TRANSMIT LIGHT THROUGH THE APPARATUS DESIGNED FOR OPTICAL SYSTEM COHERENCE TESTING
2404
OBSERVE INTERFERENCE PATTERNS FROM THE TRANSMITTED LIGHT WITH THE MEANS TO OBSERVE INTERFERENCE PATTERNS
2406

METHOD FOR OPTICAL SYSTEM COHERENCE TESTING

This application is a continuation-in-part of U.S. application Ser. No. 09/783,406, filed Feb. 15, 2001, now abandoned, which claims the benefit of U.S. Provisional Application No. 60/182,510, filed Feb. 15, 2000.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention is generally related to testing and determining the quality and coherence of a laser beam for use in photolithography systems.

2. Related Art

The ability to fabricate integrated circuit chips with increasingly smaller feature sizes depends upon continual evolution of photolithographic methods. Typically, a light source is used to illuminate a mask (reticle) so that a pattern is transferred into photoresist applied to an underlying semiconductor wafer. Machines that performs this operation are referred to as wafer steppers or wafer scanners. In order to achieve an accurate representation of the reticle pattern at submicron dimensions on the photoresist, it is necessary to use a light source that can support both a high degree of resolution and depth of focus. This requirement has led to the use of lasers as light sources for photolithographic applications.

However, the use of laser light for photolithography is not without its drawbacks. The high degree of coherence in the light produced by a laser gives rise to situations whereby interference among rays within the beam can produce a random distribution of the intensity of the light within a cross section of the beam. This random distribution of light intensity is known as speckle. Speckle adversely affects the development of the photoresist and therefore has been the subject of a myriad of corrective efforts. As speckle is an unwanted by product of the coherent property of laser light, the ability to measure coherence is a useful first step in correcting for speckle.

Coherence of a beam of light occurs when the rays within the beam travel parallel to one another and their corresponding wavefronts remain in phase over time. The extent to which these qualities are achieved is referred to as the degree of coherence. Often coherence is viewed as having two components: temporal (or longitudinal) coherence and spatial coherence. Temporal coherence measures deviations in frequency about a nominal frequency. Spatial coherence is a measure of how collimated a beam is. If a beam is highly collimated, the phases of its wavefronts are nearly identical at a given cross section of the beam.

Interference is a phenomenon that occurs when coherent beams of light overlap or intersect. Waves of light consist of oscillating fields of electric and magnetic energy. When beams of light overlap or intersect, the intensity of the light at the points of intersection is a function of the interaction among the fields of electric and magnetic energy at those points. The nature of this interaction depends upon the degree of coherence of the intersecting beams. Where the intersecting beams have a high degree of coherence, the intensity of the light at the points of intersection is proportional to the square of the vector sum of the amplitudes of the fields of electric and magnetic energy. However, if the intersecting beams are highly incoherent, the intensity of the light at the points of intersection is proportional to the sum of the square of the amplitudes of the fields of electric and magnetic energy. Therefore, if coherent beams are substantially in phase at the points of intersection, the intensity of the light is greater than the contribution of each individual beam. The points of intersection appear brighter than their surroundings. This is referred to as constructive interference. However, if coherent beams are significantly out of phase at the points of intersection, the intensity of the light is lesser than the contribution of each individual beam. The points of intersection appear dimmer than their surroundings. This is referred to as destructive interference.

As interference is a phenomenon produced by the interaction of coherent beams of light, analysis of an interference pattern created when two portions of a coherent beam of light are made to interfere with each other can be used to measure the degree of coherence. Typically, the degree of coherence is expressed as a coherence length, relating to the distance of separation, in time or space, between the two portions of the coherent beam of light creating the interference pattern. Coherence length has traditionally been measured using interferometers. Interferometers operate by splitting a coherent beam of light into two portions and later recombining the two portions to observe the resulting interference pattern. To test for temporal (longitudinal) coherence, the path length of one of the portions is extended to impart a delay in time. For spatial coherence, each portion is extracted from a separate area within the cross section of the beam. While measuring the intensity of the constructive interference areas within the interference pattern, the distance of separation is increased until the intensity falls below a specific figure of merit. The distance of separation at this point is the coherence length. The figure of merit is usually given as a percentage of the maximum intensity measured, but other figures of merit can also be used. Typical cutoff percentages are based on exponential decay or points where intensity or power are half of their maximum measured values.

Classic designs of interferometers include the Michelson, the Fabry-Perot, and the Fizeau. These are well known in the art. These instruments make use of movable arrangements of beam splitters, mirrors, and half-silvered mirrors to manipulate the paths of the beams. Much effort in the art has been expended to improve these basic designs. Ironically, where in photolithography it is desirable to reduce coherence, efforts to develop a high quality interferometer based on the classic designs seek the ability to measure coherence in real time so that it can be increased for use in high quality interferometer calibration. Where lasers are used for photolithography, the classic designs have several disadvantages: (1) the susceptibility of the instrument to inaccuracies arising from vibrations induced not only by moving parts, but also by the introduction of purge gases that, depending upon the wavelength of the light, may be needed to minimize absorption along the optical paths; (2) the difficulty of controlling the precise position of moving parts of the instrument; (3) the possibility that disassembly of optical train parts can change preset alignments; (4) the inherently fragile nature of the design; (5) the complexity involved in fabricating parts for the instrument; and (6) the expense incurred in manufacturing a sensitive instrument.

What is needed is an instrument that: (1) is insensitive to vibrations; (2) has no moving parts; (3) minimizes the extent of disassembly of optical train parts; (4) is inherently robust in design; (5) is simple to manufacture; and (6) is inexpensive. What is also needed is an instrument that can readily support real time measurement of coherence so that be increased for use in high quality interferometer calibration.

SUMMARY OF THE INVENTION

The present invention is directed at a coherence test reticle or lithographic plate, and a method for testing the coherence of a laser beam using the test reticle. The quality or coherence of the laser beam is measured by illuminating the test reticle and then recording and/or analyzing the optical patterns generated by the illumination.

The technique was designed for, but not limited to, the characterization of laser-based systems via the detection of optical radiation modulated by transmissive, reflective and diffractive patterns printed on a reticle or lithographic plate designed specifically for this purpose.

The novelty and advantages over the prior art are insensitivity to vibration, alignment, and multi-path differences of classical interferometric coherence measurement techniques. Spatial coherence and longitudinal or temporal coherence can be measured independently. Vertical and horizontal coherence can be measured independently. The technique is focus error insensitive. That is to say, that focus errors will be recorded by the technique in a deterministic fashion and can be removed from the data.

The robustness and convenience of the technique is driven by the single plate with no optical alignment, making the technique easily implemented in the field.

The multiplexing of the feature orientations, sizes and line types, and feature locations allows for the determination of coherence parameters as a function of position in the beam.

BRIEF DESCRIPTION OF THE FIGURES

The accompanying drawings, which are incorporated herein and form part of the specification, illustrate the present invention and, together with the description, further serve to explain the principles of the invention and to enable a person skilled in the pertinent art to make and use the invention.

FIG. **1** demonstrates diffraction of light through an opening in an opaque plane.

FIG. **2** shows the intersection of light diffracted through a pair of openings in opaque plane P **104**.

FIG. **3** shows the intersections of light diffracted through three pairs of openings in opaque plane P **104**.

FIG. **4** shows a series of planes parallel to opaque plane P **104** at the points of the intersections of the light diffracting through the three pairs of openings shown in FIG. **3**.

FIG. **5** shows the intersections of light diffracted through a pair of continuous openings in opaque plane P **104**.

FIG. **6** shows the intersection of light diffracted through a pair of openings in an opaque plane wherein the path lengths of the two beams are unequal.

FIG. **7** shows the intersections of light diffracted through a pair of continuous openings in opaque plane P_t **602** wherein the path lengths of the two beams are unequal.

FIG. **8** shows an apparatus embodiment of the present invention.

FIG. **9** shows the embodiment of FIG. **8** with a diffraction grating pattern arranged to diffract light in a horizontal direction **902**.

FIG. **10** shows the embodiment of FIG. **8** in which elongated areas **808** and **810** have been replaced by elongated areas **1002** and **1004** which are rotated 90 degrees, meet at point **1006**, and have a grating pattern arranged to diffract light in a vertical direction **1008**.

FIG. **11** shows an embodiment that combines the teachings of FIGS. **9** and **10** and has a diffraction grating pattern arranged to diffract light in both a horizontal and a vertical direction **1102**.

FIG. **12** shows the embodiment of FIG. **8** with a diffraction grating pattern with one measure of pitch **1202** associated with one elongated area **808** and another diffraction grating pattern with another measure of pitch **1204** associated with the other elongated area **810**.

FIG. **13** shows the embodiment of FIG. **8** in which the widths of elongated areas **808** and **810** are unequal.

FIG. **14** shows the embodiment of FIG. **8** in which elongated areas **808** and **810**, aligned symmetrically with respect to the orientation of light from the optical system, have been replaced by elongated areas **1402** and **1404**, aligned asymmetrically with respect to the orientation of light from the optical system.

FIG. **15** shows the embodiment of FIG. **8** in which straight elongated areas **808** and **810** have been replaced by elongated areas **1502** and **1504** which have curved shapes.

FIG. **16** shows an embodiment that extends the teaching of FIG. **11** to a diamond shape **1602** and has a diffraction grating pattern arranged to diffract light in both a horizontal and a vertical direction **1604**.

FIG. **17** shows the embodiment of FIG. **16** in which the diamond shape is repeated at other locations.

FIG. **18** shows typical dimensions of a diamond pattern for use with 157 nm light.

FIG. **19** shows a typical interference pattern created by light diffracted through a diamond pattern that has a diffraction grating pattern arranged to diffract light in a horizontal direction.

FIG. **20** shows a closeup of an interference zone.

FIG. **21** demonstrates a practical embodiment of the present invention.

FIG. **22** demonstrates another practical embodiment of the present invention.

FIG. **23** shows a practical embodiment of the present invention **2302** mounted in a section of tube in the optical system **2304**.

FIG. **24** shows an operational flow diagram of a method of the present invention.

A preferred embodiment of the invention is described with reference to the figures where like reference numbers indicate identical or functionally similar elements. Also in the figures, the left most digit(s) (either the first digit or first two digits) of each reference number identify the figure in which the reference number is first used.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Overview

The present invention avoids the drawbacks of the classical interferometer by exploiting another phenomenon of waves of light: diffraction. Diffraction refers to a property of waves that causes them to spread and bend as they pass through small openings or around barriers. FIG. **1** demonstrates diffraction of light through an opening in an opaque plane. For an opening **102** of a known width w in an opaque plane P **104** and an incident beam of light L **106** of a given wavelength λ, the angle of diffraction θ **108** of light diffracting through the opening is defined by the following relationship:

$$w\sin(\theta)=\lambda \qquad \text{Eq.(1)}$$

FIG. **2** shows the intersection of light diffracted through a pair of openings in opaque plane P **104**. Where opaque plane P **104** has two openings **102** and **202**, each of width w, that are separated by a known space s **204**, Eq. (1) can be used to determine a distance d **206** at which light diffracted through the two openings **102** and **202** will intersect. If the incident beam of light L **106** is coherent, then an interference pattern may form at the distance d **206** where the light diffracting through the two openings intersect I **208**. Conversely, for a known width w, a given wavelength λ, a known angle of diffraction θ **108**, and a specific distance d **206**, this equation can also be used to determine the separation of the space s **204**.

FIG. **3** shows the intersections of light diffracted through three pairs of openings in opaque plane P **104**. Openings **102** and **202** are the same openings shown on FIG. **2**. As they are separated by space s **204**, light diffracted through openings **102** and **202** will intersect at point I **208**, which is distance d **206** away from opaque plane P **104**. Above openings **102** and **202** are another pair of openings, **302** and **304**. Openings **302** and **304** are separated by a space s_u **306**. Light diffracted through openings **302** and **304** will intersect at a point I_u **308**, which is a distance d_u **310** away from opaque plane P **104**. As space s_u **306** is shorter than space s **204**, distance d_u **310** is shorter than distance d **206**. Below openings **102** and **202** are another pair of openings, **312** and **314**. Openings **312** and **314** are separated by a space s_l **316**. Light diffracted through openings **312** and **314** will intersect at a point I_l **318**, which is a distance d_l **320** away from opaque plane P **104**. As space s_l **316** is longer than space s **204**, distance d_l **320** is longer than distance d **206**.

FIG. **4** shows a series of planes parallel to opaque plane P **104** at the points of the intersections of the light diffracting through the three pairs of openings shown in FIG. **3**. Light diffracting through openings **302** and **304** intersects at point I_u **308**, which lies in plane P_u **402**. Light diffracting through openings **102** and **202** intersects at point I **208**, which lies in plane P_m **404**. Light diffracting through openings **312** and **314** intersects at point I_l **318**, which lies in plane P_l **406**.

Analysis of an interference pattern created when two portions of a coherent beam of light are made to interfere with each other can be used to measure the degree of spatial coherence. In FIG. **4**, interference patterns appear at point I_u **308** in plane P_u **402**, at point I **208** in plane P_m **404**, and at point I_l **318** in plane P_l **406**. Typically, the degree of spatial coherence is expressed as a spatial coherence length, relating to the distance of separation between the two portions of the coherent beam of light creating the interference pattern. By comparing the intensity of the constructive interference areas within each of the interference patterns with a specific figure of merit, the spatial coherence length can be determined. Thus, if the intensity of the interference pattern at point I_u **308** and at point I **208** is greater than the specific figure of merit, while the intensity of the interference pattern at point I_l **318** is less than the specific figure of merit, then the spatial coherence length has been determined to be greater than the distance of separation space s **204**, but less than the distance of separation space s_l **316**.

FIG. **5** shows the intersections of light diffracted through a pair of continuous openings in opaque plane P **104**. FIG. **5** demonstrates the logical extension of the arrangement being developed in FIGS. **3** and **4**. Continuous openings **502** and **504**, each of width w, intersect at a point **506** and diverge linearly to form an inverted "V" shape. This arrangement has the effect of a continuous array of pairs of openings in opaque plane P **104**. Light diffracted through continuous openings **502** and **504** intersects along a continuous series of points along a line segment **508**. Line segment **508** originates at point **506** and extends downward and away from opaque plane P **104**. Continuous openings **502** and **504** and line segment **508** form a tetrahedron shape. The infinite series of points of intersection along line segment **508** corresponds to an infinite series of planes parallel to opaque plane P **104**. With this arrangement, a continuum of interference patterns can be created and the intensity of their respective constructive interference areas can be measured and compared with a specific figure of merit to determine accurately the spatial coherence length of the incident beam of light L **106**. Thus, if the intensity of the interference pattern at point I_s **510** equals the specific figure of merit, then the spatial coherence length has been determined accurately to be the distance of separation space s_s **512**.

The aforementioned description pertains to the measurement of spatial coherence. To test for temporal (longitudinal) coherence, the path lengths of light diffracted through a pair of openings must be unequal at the point of intersection so that a difference in time between the two beams is imparted into the interference pattern. FIG. **6** shows the intersection of light diffracted through a pair of openings in an opaque plane wherein the path lengths of the two beams are unequal. Here, opaque plane P_t **602** has two openings **604** and **606** that are separated by a known space s_0 **608**. Opening **604** has a width w_1 and opening **606** has a width w_2, such that w_1 is larger than w_2. For an incident beam of light L **106** of a given wavelength λ, the angles of diffraction θ_1 **610** and θ_2 **612** of light diffracting through the two openings **604** and **606** are defined by the following relationship:

$$w\sin(\theta)=\lambda \qquad \text{Eq.(1)}$$

Hence, θ_1 **610** is smaller than θ_2 **612**. The effect of this difference is to make path length l_1 **614** smaller than path length l_2 **616** so that a difference in time between the two beams is imparted into the interference pattern created at point I_o **618**.

FIG. **7** shows the intersections of light diffracted through a pair of continuous openings in opaque plane P_t **602** wherein the path lengths of the two beams are unequal. FIG. **7** demonstrates a combination of the principles depicted in FIGS. **5** and **6**. Continuous openings **702** and **704** have widths, respectively, of w_1 and w_2, such that w_1 is larger than w_2. Continuous openings **702** and **704** intersect at a point **706** and diverge linearly to form an inverted "V" shape. This arrangement has the effect of a continuous array of pairs of openings in opaque plane P_t **602**. Light diffracted through continuous openings **702** and **704** intersects along a continuous series of points along a line segment **708**. Line segment **708** originates at point **706** and extends downward and away from opaque plane P_t **602**. Continuous openings **702** and **704** and line segment **708** form a tetrahedron shape. The infinite series of points of intersection along line segment **708** corresponds to an infinite series of planes parallel to opaque plane P_t **602**. With this arrangement, a continuum of interference patterns can be created such that the difference in time between the two beams is zero at point **706**, increases as line segment **708** extends downward and away from opaque plane P_t **602**, and is imparted into the continuum of interference patterns. The intensity of their respective constructive interference areas can be measured and compared with a specific figure of merit to determine accurately the temporal (longitudinal) coherence length of the incident beam of light L **106**. Thus, if the intensity of the interference pattern at point I_t **710** equals the specific figure of merit, then the temporal (longitudinal) coherence length has been determined accurately to be the distance of separation space s_t **712**.

Apparatus

FIG. **8** shows an apparatus embodiment of the present invention. The apparatus comprises a transparent plate **802** wherein the transparent plate **802** is made to be opaque on at least one surface **804** in all areas except for an area of a pattern **806**. Where the apparatus will be used in photolithography, transparent plate **802** can be a reticle. One skilled in the art will recognize the variety of physical forms that transparent plate **802** can assume.

The pattern comprises two elongated areas **808** and **810** each having at least one width of a dimension that would cause coherent light from the optical system to diffract upon transmitting through the area of the pattern **806**. The two elongated areas **808** and **810** are joined at a common point **812** and diverge from the common point **812** to form an angle.

FIG. **9** shows the embodiment of FIG. **8** with a diffraction grating pattern arranged to diffract light in a horizontal direction **902**.

FIG. **10** shows the embodiment of FIG. **8** in which elongated areas **808** and **810** have been replaced by elongated areas **1002** and **1004** which are rotated 90 degrees, meet at point **1006**, and have a grating pattern arranged to diffract light in a vertical direction **1008**.

FIG. **11** shows an embodiment that combines the teachings of FIGS. **9** and **10** and has a diffraction grating pattern arranged to diffract light in both a horizontal and a vertical direction **1102**.

The inclusion of a diffraction grating pattern within the area of the pattern **806** allows for the area of the pattern **806** to have a larger width while maintaining or improving the degree of diffraction. This permits a greater amount of light to transmit through the area of the pattern **806** so that variations in intensity within the interference pattern are more pronounced and hence easier to measure. One skilled in the art will recognize that the diffraction grating pattern can be realized as an amplitude grating or a phase grating.

The diffraction grating pattern arranged to diffract light in a horizontal direction **902** allows for horizontal spatial coherence to be measured independent of vertical spatial coherence. The diffraction grating pattern arranged to diffract light in a vertical direction **1002** allows for vertical spatial coherence to be measured independent of horizontal spatial coherence. The diffraction grating pattern arranged to diffract light in both a horizontal and a vertical direction **1102** allows for horizontal and vertical spatial coherence to be measured simultaneously. The ability to measure both horizontal and vertical spatial coherence is an important advantage of the present invention because excimer lasers used in photolithograpy often have different horizontal and vertical spatial coherence lengths.

FIG. **12** shows the embodiment of FIG. **8** with a diffraction grating pattern with one measure of pitch **1202** associated with one elongated area **808** and another diffraction grating pattern with another measure of pitch **1204** associated with the other elongated area **810**. This arrangement allows for the path lengths of light diffracted through elongated areas **808** and **810** to be unequal so that temporal (longitudinal) coherence can be measured.

FIG. **13** shows the embodiment of FIG. **8** in which the widths of elongated areas **808** and **810** are unequal. This arrangement allows for the path lengths of light diffracted through elongated areas **808** and **810** to be unequal so that temporal (longitudinal) coherence can be measured.

FIG. **14** shows the embodiment of FIG. **8** in which elongated areas **808** and **810**, aligned symmetrically with respect to the orientation of light from the optical system, have been replaced by elongated areas **1402** and **1404**, aligned asymmetrically with respect to the orientation of light from the optical system. This arrangement allows for the path lengths of light diffracted through elongated areas **1402** and **1404** to be unequal so that temporal (longitudinal) coherence can be measured.

FIG. **15** shows the embodiment of FIG. **8** in which straight elongated areas **808** and **810** have been replaced by elongated areas **1502** and **1504** which have curved shapes. This arrangement enables coherence length to be determined by the present invention in a non-linear manner. One skilled in the art will recognize that the curvature of elongated areas **1502** and **1504** could be concave or convex and could be designed so that coherence length is determined in a logarithmic or any other desired manner.

FIG. **16** shows an embodiment that extends the teaching of FIG. **11** to a diamond shape **1602** and has a diffraction grating pattern arranged to diffract light in both a horizontal and a vertical direction **1604**.

FIG. **17** shows the embodiment of FIG. **16** in which the diamond shape is repeated at other locations. Transparent plate **802** in FIG. **17** includes four diamond patterns: **1710**, **1720**, **1730**, and **1740**. Each diamond pattern includes a diffraction grating pattern arranged to diffract light in both a horizontal and a vertical direction. Respectively, these diffraction grating patterns are: **1712**, **1722**, **1732**, and **1742**. Each diamond pattern includes an opaque center. Respectively, these opaque centers are: **1714**, **1724**, **1734**, and **1744**. Finally, the four diamond patterns are surrounded by an opaque background **1750**.

FIG. **18** shows typical dimensions of a diamond pattern for use with 157 nm light.

FIG. **19** shows a typical interference pattern created by light diffracted through a diamond pattern that has a diffraction grating pattern arranged to diffract light in a horizontal direction. Broad white band **1902** corresponds to zero order diffraction light, that light that passes directly through the grating pattern without being diffracted. Opaque diamond interior **1904** provides a dark background wherein diffracted light can appear. Narrow white band **1906** corresponds to first order diffracted light. Interference zones **1908** and **1910** are the areas where interference patterns can be observed and measured.

FIG. **20** shows a closeup of an interference zone.

Returning to FIG. **17**, one skilled in the art will appreciate that the diamond patterns **1710**, **1720**, **1730**, and **1740** allow for the light beam to be sampled for coherence at a variety of locations within a cross section of the beam. The diamond pattern facilitates testing for both horizontal and vertical spatial coherence. Diffraction grating patterns **1712**, **1722**, **1732**, and **1742** cause incident light to diffract to a larger degree than would occur in their absence. This enables interference zones to occur in a plane closer to transparent plate **802** so that less of the intensity of the light is lost to absorption. Opaque centers **1714**, **1724**, **1734**, and **1744** provide a dark background on which the interference zones can appear for observation and measurement. In FIG. **17**, transparent plate **802** also provides for temporal (longitudinal) coherence to be measured. Recall from FIG. **1** that diffracted light bends in both directions about the line in the plane perpendicular to the plane of the opening. So, for example, if diffractive grating pattern **1712** has a measure of pitch different from the measure of pitch of diffractive grating pattern **1722**, then light diffracted outward (towards opaque background **1750**) from diamond pattern **1710** and from diamond pattern **1720** will intersect at a point such that the two diffracted beams will have different path lengths. An interference zone at this point of intersection can be used to measure temporal (longitudinal) coherence. One skilled in the art will recognize other methods taught herein that can be used to facilitate measuring temporal (longitudinal) coherence with a transparent plate **802** as shown in FIG. **17** and with other arrangements.

Where surface **804** of transparent plate **802** on FIG. **17** is placed in the path of an incident beam of light at an angle slightly deviating from perpendicular, a collection of interference zones will be created by diamond patterns **1710**, **1720**, **1730**, and **1740** at a variety of distances from transparent plate **802** that the intensity of the constructive interference portion of the collections of interference zones can be measured and compared to a specific figure of merit to measure coherence. Because interference patterns will occur on a continuum of distances, the apparatus does not require precise spacing between it and the plane where interference patterns will be observed or recorded. That is to say, the apparatus is relatively insensitive to focus errors because inaccuracies in spacing will be observed or recorded so that they can readily be detected and extracted from measured data. The multiplexing of various diffractive grating pattern designs enables coherence measurements to be associated with specific points in the cross section of the incident beam.

FIG. **21** demonstrates a practical embodiment of the present invention. Diffractive reticle **2102** corresponds to a transparent plate **802** of the type described above. A spacing device is used to create distance between diffractive reticle **2102** and a plane where interference patterns can be observed or recorded. In FIG. **21**, the spacing device is a piezoelectric spacer **2104** (here comprising four piezoelectric modulators). Voltage can be applied to piezoelectric spacer **2104** in a manner so as to create a slight angle from perpendicular between the plane of diffractive reticle and the plane where interference patterns will be observed or recorded. Alternatively, voltage can be applied to piezoelectric spacer **2104** in a manner so that the plane where interference patterns will be observed or recorded "walks away" or "walks toward" the plane of diffractive reticle **2102**. This is particularly useful for real time observations.

Where the interference patterns are to be recorded, a recording medium **2106** is put in place. One skilled in the art will recognize that a variety of recording media, both photographic and electronic, can be used. This includes, but is not limited to: photographic films, holographic films, photorefractive media, photopolymers, photoresist, position sensitive devices, charged coupled devices, photodiodes, CMOS image sensors, and other electronic image detection technologies.

Demodulator reticle **2108** contains a diffractive grating pattern of the same measure of pitch as used in diffractive reticle **2102**. Alternatively, demodulator reticle **2108** can be an electro-optic demodulating device or an acousto-optic demodulating device. By placing demodulator reticle **2108** downstream of piezoelectric spacer **2104**, intersecting diffracted rays can be made to travel parallel and/or coincidental paths so that interference patterns can be visually observed in real time or recorded on recording medium **2106**.

A phosphorous film **2110** can also optionally be placed before recording medium **2106**. Where incoming light is at X-ray wavelengths, phosphorous film **2110** is useful in protecting electronic image sensors and enables the light to be visually observable.

FIG. **22** demonstrates another practical embodiment of the present invention. Here the spacing device is a piezoelectric transmissive crystal **2204**. Voltage can be applied to piezoelectric transmissive crystal **2204** in a manner so as to create a slight angle from perpendicular between the plane of diffractive reticle **2202** and the plane where interference patterns will be observed or recorded **2206**. Alternatively, voltage can be applied to piezoelectric transmissive crystal **2204** in a manner so that the plane where interference patterns will be observed or recorded **2206** "walks away" or "walks toward" the plane of diffractive reticle **2202**. This is particularly useful for real time observations.

A more simple and less expensive spacing device can be realized by using a wedge-shaped transmissive crystal.

One skilled in the art will appreciate that the practical embodiments presented above and demonstrated in FIGS. **21** and **22** are, in comparison with classical design interferometers: insensitive to vibrations, inherently robust in nature, simple to manufacture, and inexpensive.

For use in testing photolithographic optical systems, the apparatus of these practical embodiments can be mounted in a tube such that the test tube can be inserted in place of an existing section of tube in the optical system. FIG. **23** shows a practical embodiment of the present invention **2302** mounted in a section of tube in the optical system **2304**. This minimizes the extent of disassembly of optical train parts.

Method

FIG. **24** shows an operational flow diagram of a method of the present invention. At a step **2402**, a light source, in an optical system, is aligned with an apparatus designed for optical system coherence testing and with a means to observe interference patterns. At a step **2404**, light is transmitted through the apparatus designed for optical system coherence testing. At a step **2406**, interference patterns from the transmitted light are observed with the means to observe interference patterns.

So that the means to observe interference patterns can include interference patterns at a variety of distances from the apparatus designed for optical system coherence testing, it is often desired that the alignment be oriented so that light incident upon the apparatus designed for optical system coherence is at a non-perpendicular angle. Alternatively, the alignment can be oriented so that light incident upon the means to observe interference patterns is at a non-perpendicular angle. In various embodiments, this latter method can be provided by placing between the apparatus designed for optical system coherence testing and the means to observe interference patterns any of the following: a wedge-shaped transmissive crystal, a transmissive piezoelectric crystal, or a piezoelectric spacer. One skilled in the art will recognize other means by which the alignment can be oriented so that light incident upon the means to observe interference patterns is at a non-perpendicular angle.

The apparatus designed for optical system coherence testing can be designed to test for spatial coherence independent of tests for temporal (longitudinal) coherence. It can be designed to test for horizontal spatial coherence independent of tests for vertical spatial coherence. It can be designed to test for horizontal and vertical spatial coherence simultaneously. It can be designed to minimize the extent of necessary disassembly of the optical system.

The means to observe interference patterns can include, but is not limited to, visual observation facilitated by a demodulator reticle or a recording medium. A variety of recording media, both photographic and electronic, can be used. This includes, but is not limited to: photographic films, holographic films, photorefractive media, photopolymers, photoresist, position sensitive devices, charged coupled devices, photodiodes, CMOS image sensors, and other electronic image detection technologies.

CONCLUSION

While an embodiment of the present invention has been described above, it should be understood that it has been presented by way of example only, and not limitation. It will be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined in the appended claims. Thus, the breadth and scope of the present invention should not be limited by the above-described exemplary embodiment, but should be defined only in accordance with the following claims and their equivalents.

What is claimed is:

1. A method for optical system coherence testing, comprising the steps of:

a. in an optical system, aligning a light source with an apparatus designed for optical system coherence testing and with a means to observe interference patterns;

b. transmitting light through the apparatus designed for optical system coherence testing; and

c. observing interference patterns from said transmitted light with the means to observe interference patterns;

wherein said aligning provides that light incident upon the apparatus designed for optical system coherence testing is at a non-perpendicular angle.

2. The method of claim **1**,

wherein the means to observe interference patterns is a recording medium.

3. The method of claim **2**, wherein the recording medium is photographic.

4. The method of claim **2**, wherein the recording medium is electronic.

5. A method for optical system coherence testing, comprising the steps of:

a. in an optical system, aligning a light source with an apparatus designed for optical system coherence testing and with a means to observe interference patterns;

b. transmitting light through the apparatus designed for optical system coherence testing; and

c. observing interference patterns from said transmitted light with the means to observe interference patterns;

wherein said aligning provides that light incident upon the means to observe interference patterns is at a non-perpendicular angle.

6. The method of claim **5**, wherein said aligning is provided by a wedge-shaped transmissive crystal.

7. The method of claim **5**, wherein said aligning is provided by a transmissive piezoelectric crystal.

8. The method of claim **5**, wherein said aligning is provided by a piezoelectric spacer.

9. The method of claim **5**, wherein the means to observe interference patterns is a recording medium.

10. The method of claim **9**, wherein the recording medium is photographic.

11. The method of claim **9**, wherein the recording medium is electronic.

12. A method for optical system coherence testing, comprising the steps of:

a. in an optical system, aligning a light source with an apparatus designed for optical system coherence testing and with a means to observe interference patterns;

b. transmitting light through the apparatus designed for optical system coherence testing; and

c. observing interference patterns from said transmitted light with the means to observe interference patterns;

wherein the apparatus designed for optical system coherence testing simultaneously tests for both horizontal and vertical spatial coherence.

13. The method of claim **12**, wherein the apparatus designed for optical system coherence testing tests for temporal (longitudinal) coherence.

14. A method for optical system coherence testing, comprising the steps of:

a. in an optical system, aligning a light source with an apparatus designed for optical system coherence testing and with a means to observe interference patterns;

b. transmitting light through the apparatus designed for optical system coherence testing; and

c. observing interference patterns from said transmitted light with the means to observe interference patterns;

wherein the means to observe interference patterns is visual observation facilitated by a demodulator reticle.

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